VOLUME XXXIX NUMBER 7

THE
JOURNAL OF GEOLOGY

October-November 1931

THE WANING OF THE LAST CONTINENTAL GLACIER IN DENMARK AS ILLUSTRATED BY VARVED CLAY AND ESKERS

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ABSTRACT

A study of the circumstances under which eskers and varved clay in southeastern Zealand, Denmark, were built has revealed that the ice remained as a stagnant body for many years before it finally melted away. Moraines, earlier regarded as deposits of the ice border, were deposited underneath the ice along a line of demarcation between the moving ice and a broad stagnant ice-border zone. This line was found in places probably more than 50 miles inside the true ice border. Four chains of eskers have been studied, and it has been shown that they are composed of similar successions of different links and that the corresponding links in each of the four chains were deposited contemporaneously just outside or partly inside the said line. The chains are composed of a series of bows, each deposited during a single year. This has led to a determination of the inward migration of the line during ten succeeding years, and has resulted in an exact relative dating of the deposits and the events during the late Pleistocene development of that region.[1]

INTRODUCTION

The question of how the ice, which in Pleistocene time covered the northern part of Europe and North America, finally melted away, is one of the most fundamental of all in an attempt to explain the physiography of the deposits of that time. It has ordinarily been suggested that the ice front retreated as an ice wall able to push up moraines. It has been proposed, however, that the ice remained for a long time as a stagnant body—an idea recently carried to an extreme by R. F. Flint. In some cases the first conception is without

[1] A more detailed paper in the English language on the subject will appear in the publications of the Danish Geological Survey.

doubt correct; in others the second is the only acceptable one. Thus the question is merely to decide which has been the case in any particular region and how to prove it.

FIG. 1.—Map of Denmark (excepting Bornholm). It shows the limit of the last glaciation (*I*) and some of the more outstanding younger moraines, of which the East-Jutlandian ice-border zone is important (*II*). Outside the limit of the last glaciation are shown the old moraines from the preceding glaciation (black areas) with the glaciofluvial plains (stippled area). The river in Zealand is the Susaa River, where the investigation was carried out.

To attain the correct explanation of the glacial and glaciofluvial features it is necessary to concentrate the investigation on the stratified deposits—sand plains, valley trains, kames, eskers, and varved clays. In many regions the glaciofluvial deposits were laid down between walls of ice, but they do not show any evidence of

pressure of the ice, so that the ice must be regarded as stagnant. This simply means, however, that moving of the ice has not been proved in spite of careful investigation of available cuts.

Thus in discussing the development of a certain region during the waning of the last ice sheet we must distinguish two major stages (see Figs. 2–4). First there was a stage when the ice was moving forward, able to push up moraines and other deposits underneath the ice. After this there was a time when the ice practically ceased to move, and the second major stage followed. During this stage the ice was stagnant, "dead," and was not moving forward any longer. Melting on the surface, the ice lost in thickness from year to year until finally the last scattered remains disappeared. The main problem is thus to decide during which stage the deposition of the moraines, eskers, etc., took place.

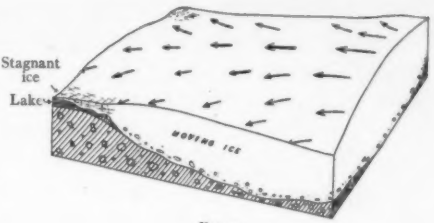

FIG. 2

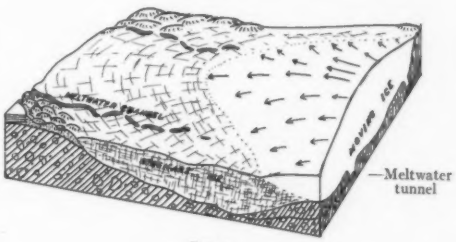

FIG. 3

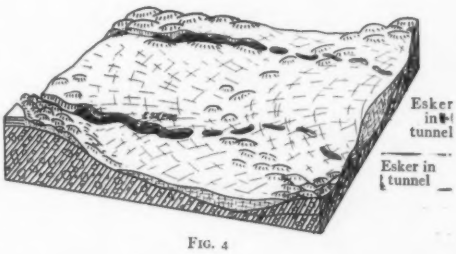

FIG. 4

FIGS. 2–4.—Block diagrams, showing schematically how the ice probably melted away in Eastern Denmark. Moving ice indicated by arrows, stagnant ice by crossed lines, varved clay by horizontal ruling, and sand by dots. Length of block about twenty miles. Fig. 2 shows the time when the ice cover in the upland was stagnant and thinned by melting. It was lifted and a subglacial lake was born underneath the ice. Behind and beside the upland is the ice still pressing forward. Fig. 3 shows the same region some years later. Most of the ice is stagnant, but the moving ice still covers a certain part of the region. The tunnels underneath the moving ice continue as channels in the stagnant ice, where eskers are being deposited. In Fig. 4 all the ice within the block is stagnant and the eskers are deposited farther east and can be seen in the tunnel valleys.

Of greatest importance is the line of demarcation between the moving and the stagnant ice-border zone (hereafter described as "line"). Along and inside this line prominent moraine ridges were pushed up and drumlins formed, while inactive, stagnant ice still lay to an unknown extent outside the line. The line remained along the moraine ridge for a longer or shorter period after which it started to migrate inward from year to year, stopping along new lines. The lines along which the retreating ice border was formerly supposed to have stood for some time are, in many places at least, lines along which the line of demarcation remained. In some places the true ice border was identical with this line; in others, and perhaps in the majority of cases, the real ice border was far outside the line. On account of its inactivity, however, the position of the true ice border cannot be ascertained, but can sometimes be roughly estimated. In some regions of Denmark it can be proved that moraine ridges were pushed up about 50 miles inside the ice border, so that the stagnant border zone was at least that wide. The same was, however, the case in all places where subglacial features, till-plains, drumlins, eskers, etc., are found, as no traces of a moving ice front are here seen.

There is one point which must be made clear before we can understand the conditions within the waning ice. In the forward-moving portion all crevasses formed in the lower part of the ice were quickly pressed together and thus the melt water had difficulty in flowing through. The tunnels underneath were compressed and narrowed so that the water flowed under high pressure and eroded a valley in the till beneath, where the ice movement was slowest. But in the stagnant ice the tunnels were no longer compressed and the melt water escaped more easily to the ice border. In this part of the ice, particularly, we can refer to a major "water table," which sloped more or less in the direction of flow. This water table may be treated as an ordinary water table in sand and gravel, keeping in mind, however, that ice is lighter than water.

When the ice lost its movement, this water table dropped considerably, and every time the melt water found a lower escape it dropped again. The water table represents the ultimate upper limit of deposition of glaciofluvial material, and a flat top developed upon

such deposits indicates that they reached the water table and not necessarily the surface of a lake as one might suppose. An important thing to take into consideration is that when the surface of the ice melted down almost to the water table, a tendency to lift occurred in the whole border zone. Thus there came to be a space underneath the stagnant ice filled with rushing and irregularly streaming water, and here it seems we have the conditions under which kames and pitted plains were built. For as long as the water table lay near the ice surface, the depositing streams naturally flowed underneath the stagnant ice, which more or less floated on the melt water. Thus there is in reality no limit for the breadth of the tunnels underneath the ice.

The glaciofluvial deposits very often appear, at least, to be undisturbed, and thus evidence that these deposits were formed on or within the ice is lacking. The topographic expression of pitted plains and kames with undisturbed layers does not originate from a collapse of the whole deposit, but the surface is largely a cast of the under surface of the ice at the time when the deposition ceased. Accordingly the ice in the kettles must have been covered by a rather thin veneer of drift, and the ice-contact slopes must be regarded as due to a slumping of gravel only in cases where such disturbance can actually be proved. In most cases it appears that the present slopes are largely the original ones.

THE ICE-DAMMED LAKES IN ZEALAND

The varved clay in Denmark was not measured successfully until very recently in spite of the fact that Professor de Geer in Stockholm started the investigation twenty-five years ago. Antevs succeeded in two places (De Geer, 1926[1]; S. A. Andersen, 1928[2]). The difficulty has been that varves were laid down in most of the Danish ice-dammed lakes during three summer months and several of the more outstanding clay layers deposited during a single night, or a

[1] Gerard de Geer, "On the Solar Curve as Dating the Ice-Age," *Geografiska Annaler* (Stockholm), Vol. VIII.

[2] S. A. Andersen, "De danske varv," *Geologiska For. i Stockholm Fork.* (Vol. X, 1928); Ueber die danischen autochtonen und allochtonen Warwen, und ueber Oszentren, Winterschichten und die Gliederung in Jahresabschnitte," *Report of the 18. Scandinavian Naturalists Congress in Copenhagen, Aug. 26–31, 1929.*

series of nights, have been mistaken for winter layers. Thus whereas De Geer reported (1926) about 400 varves from a Danish locality, there really are varves from only about twenty years (S. A. Andersen, 1928, 1929),[1] De Geer's statement of how long ago the ice retired from Denmark has so far not been proved, but the figure is certainly too high.[2]

In Eastern Denmark one does not usually find the varved clay along the seacoast or in the valleys as might be expected. Instead the clay forms small plateaus, which are the highest hills in the uplands (V. Milthers, 1922[3]; S. A. Andersen, 1928). Examining the varves one finds that the deposition took place during a period of from ten to one hundred years and that the layers are undisturbed, with the exception locally of some of the bottom ones. The lakes in which these varves were deposited must have been surrounded on all sides by stagnant ice, since the deposits now constitute the highest parts of the uplands and as the lakes must have existed for at least as long as the varves indicate (Figs. 2–4). Such a lake existed for over twenty years in the upland southwest of Soroe (see map, Fig. 5) with a water table about 300 feet above present sea level. A computation shows that this lake probably was situated more than 50 miles inside the stagnant ice border, and thus the stagnant ice-border zone must have been at least that broad. Furthermore, a detailed search for evidence of ice blocks buried underneath the clay at the time of deposition has been in vain, and thus we may assume that such exceptional lakes were born underneath the ice cover, which was lifted as the surface was lowered by melting down to the water table (Fig. 2).

THE TUNNEL VALLEYS AND THE ESKERS

The same conception of the waning of the ice sheet must be applied to understand the building of the very abundant eskers in the southeastern part of Zealand (Figs. 1 and 5). Here we find three hilly uplands, reaching to about 300–400 feet. North of Ringsted is found the Skjoldnaesholm upland, southwest of Soroe is found the Lindebjerg upland, and northeast of Naestved the Wester Egede up-

[1] *Ibid.* [2] *Op. cit.*

[3] V. Milthers, "Nordöstsjællands Geologi," *Denmark Geol. Surv.*, Ser. V, No. 3 (1922).

land. The depression between these three uplands is drained by the Susaa River to the Smaaland Sea. This river has a rather remarkable course, shaped like the letter U. The headwaters are found on

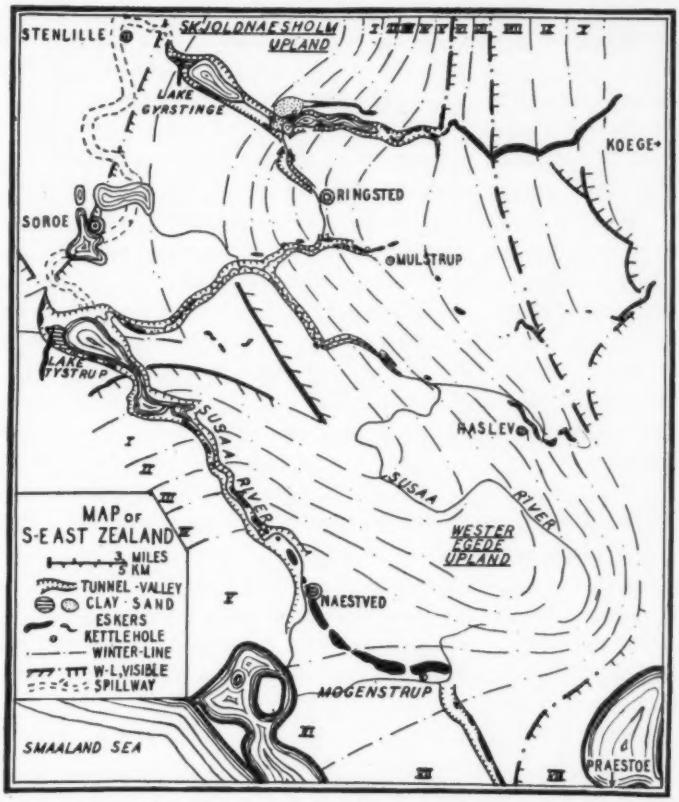

FIG. 5.—Map of Southeastern Zealand with tunnel valleys, eskers, kettleholes, and winter lines, drawn with the aid of the eskers. The visible winter lines can be traced in the terrain and have so far been regarded as ice-border features.

the east slope of the Wester Egede upland, and the upper part of the course is directed toward the northwest as far as a point southwest of Ringsted, where the river turns to the southwest and discharges into Lake Tystrup. From here the course is directed toward the

southeast, and the outlet is found south of Naestved quite close to the headwaters. The largest tributary is the Ringsted River, which drains the valleys around Ringsted.

The last ice sheet, which covered the region, came from the Baltic and moved northwestward only deflected and retarded locally by the uplands. At a certain time the active ice reached only to the region around Soroe and Stenlille, while stagnant ice still more or less covered the region farther northwestward. At this time several streams of melt water flowed underneath the moving ice and deposited large quantities of gravel, sand, and clay near Soroe and Stenlille, partly in temporary, ice-dammed lakes. The northernmost of the rivers here considered eroded underneath the ice an outstanding tunnel valley (V. Madsen, 1928)[1] which can be traced from Koege at the sound westward to a point east of Stenlille. It is called the "Koege esker valley," as the Koege esker follows the valley, and contains in its western part the two lakes, Lake Haraldsted and Lake Gyrstinge. The largest of the streams eroded the Naestved esker valley, which can be followed from Praestoe northwestward past Naestved to a point southwest of Soroe. Lake Tystrup is found in the northwestern part of this valley. The smaller Mulstrup esker valley near Mulstrup south of Ringsted runs parallel to the Koege esker valley, and continues southeastward with several interruptions. The similar Haslev esker valley passes Haslev and continues northwestward as the valley which the Susaa River follows above Lake Tystrup. The part of this valley between the inflow of the Ringsted River and Lake Tystrup is common to both of the smaller tunnel valleys, and the melt-water streams which eroded the two joining valleys were subglacial tributaries of the much larger stream, which eroded the Naestved esker valley.

After some dozens of years the ice within this region also lost its movement. The tunnels underneath the ice were not compressed any longer, and the erosion changed to deposition. Stratified material was laid down underneath the water table within the stagnant ice, usually between overhanging ice walls, and when the ice melted away the fillings of the channels remained as chains of eskers. They

[1] Victor Madsen, "Summary of the Geology of Denmark," *Denmark Geol. Surv.*, Ser. V, No. 4, p. 152.

follow very closely the above-mentioned valleys, which were eroded by the same melt-water streams as the ones which later on deposited the eskers.

This conception of the origin of the eskers is usually accepted, but it is possible to go farther in the explanation of several eskers such as those in the region mentioned. A comparison of the four tunnel valleys and the associated chains of eskers has shown that they are composed of similar successions of different links only modified according to local circumstances. To make these similarities more easily seen, we shall divide each tunnel valley and chain of esker in three major parts, which we shall further subdivide.

The first major part in the Koege esker valley includes the northwestern part containing Lake Gyrstinge. In the Naestved esker valley this part includes the basin of the northwestern half of Lake Tystrup. Both are almost pear-shaped in outline, and many of the minor details, especially the situation and distribution of the esker-hills and other stratified material, are very similar in the two valleys. The only important difference is that the southeastern end of this major part is bent toward the south in Lake Tystrup, but is straight in Lake Gyrstinge. A similar comparison of these two larger tunnel valleys with the two smaller ones reveals that the corresponding parts of the smaller ones are the tunnel valleys of the Susaa River above Lake Tystrup to its sharp turn due south of Ringsted. Local circumstances caused this major part to be long and narrow instead of short and broad as in the two larger tunnel valleys.

The second major part will be seen in all four valleys to make a right angle with the first major part, but soon it curves and takes approximately the same direction as the first major part. In the second part the narrow tunnel valley is outstandingly serpentine shaped, or really composed of five bows, which are convex toward the north or northeast and join in rather distinct angles. The interesting point is that, just as in the first major part, we are able to recognize the same fundamental development of the corresponding bows, and this is particularly true of the three northeastern tunnel valleys, although it also applies to the Naestved esker valley. In each valley the five bows have been numbered I to V. On the map, Figure 5, lines (called winterlines) are drawn through the correspond-

ing points of connection between the bows as well as at each end of the series.

In the third major part we find no real tunnel valley, but only a depression along the sides of the esker chain. This "esker-trough" is the continuation of the much deeper and broader tunnel valleys, which are more than 150 feet deep and 2 or 3 miles wide. The eskers in this part (especially the Koege esker) are clearly composed of such bows, of which we can differentiate five. In the same way as before, lines are drawn through the corresponding connecting points of the bows, which have been numbered VI to X.

Just as in the first major part, it is possible to recognize similarities within the corresponding bows in the other two major parts. These will not be discussed at any great length, but some of the most striking ones will be briefly considered in order to show to which kind they belong.

Only in a single place in the second major part is a cover or layer of till found in the stratified deposits, and this is in bow No. II in each chain. Bow No. III is characterized by an esker which disappears eastward or southeastward into the till plain just beside the tunnel valley. Of greatest importance, however, are the four esker hills southeast of Naestved and the corresponding hills in the other three chains. The four hills southeast of Naestved, which together compose the Mogenstrup esker, are as much as 150–60 feet high and 5 miles long. They correspond to four much smaller hills of the Koege esker, almost of the same outline and relative height as the hills of the Mogenstrup esker in spite of the absolute difference in size. The easternmost of the hills in both places is curved a little northward and, at its eastern end, it continues as another bow of the same size as the first, but curved the other way and making a right angle with it. The eskers continue in straight lines southeastward as far as the divide between the area draining to the Smaaland Sea and that draining to the sound. The remarkable trend of this portion of the bows has been recognized as very conspicuous in all four chains.

This outstanding similarity in the succession of the different parts in each of the four tunnel valleys can only be explained if we assume that the corresponding parts were developed contemporaneously.

Thus it is possible to point out contemporaneous hills lying as much as 45 miles away from each other.

The arrangement of the tunnel valleys and especially the eskers within bows is not without significance. If we follow along one of the better-developed parts of a chain we see that the esker is either very low or in some cases interrupted where the bows join each other. In the cuts near the point of connection we find that the material is very fine sand and silt, and an examination often reveals a layer of fine silt or even clay 1–3 or more inches thick. This is a layer deposited during the winter time, when the melt water in the tunnel almost ceased to run and the tunnel was filled with quiet water. Eastward from this point we find that the size of the material increases, and at last we reach a place where the stones are almost as large as a man's head and a few even larger. This is the "esker center," as De Geer has named it, deposited in the mouth of the melt-water tunnel during the summer time, when the stream had a swift current and was able to carry such large boulders. The finest material was carried westward and deposited as the fine sand and silt above the winter layer just mentioned. Farther eastward the material again is fine gravel and sand, and near the east end of the bow is also found fine sand and silt and the winter layer, and the esker is low and flat and in places separated from the following bow by an interruption. In other words, *each of the ten bows appears to contain the deposits from a single year*, and thus the eskers in the second and third major parts were deposited during a series of ten years, one bow in each chain during a single year.

We must regard the place where the melt water begins to drop the coarser part of its heavy load as the mouth of the melt-water tunnel. The mouths migrated backward through the ice, following the retreating line of demarcation between the stagnant and the moving ice. The lines which are drawn through the connections between contemporaneous bows, just where the winter layers are found, can be regarded as the successive positions of this line during ten succeeding winters. The ten years are given the same number as the bows, since we do not yet know how many years ago it was that deposition took place. The movement of the ice was perhaps a little oblique to the direction of the tunnel valleys, and this gave rise to

the bows. The originally straight tunnel was bent a little every summer, when the ice moved forward and the ice was compressed and swelled a little along the limit of the stagnant ice.

The movement of the ice appears at any rate to have been greatest during summer time, as is the case of present-day glaciers. The winter layers of the eskers are undisturbed as is the finer sand. The coarser material, gravel and cobblestone, however, is commonly pressed up into an anticline, which strikes more or less in the same direction as the crest of the esker. The deposited layers near the bottom were pressed up, while the deposition of the upper layers was still going on. At the close of the summer the oldest layers stood almost vertically, including as a rule a vertical core of till 1–3 feet thick or more, while the dipping of the layers decreased outward toward the sides of the esker. The disturbance here was brought to a close in the fall and new undisturbed layers were deposited east of the disturbed esker center. The anticlinal layers were some thirty years ago named "beta layers" by V. Madsen (1900).[1] The undisturbed layers discordantly superimposed upon them, or found in other parts of the esker chain, were named "alpha layers."

The kettleholes associated with the eskers occur in this region as single kettles at the connecting points between the bows. Where the esker chain passes uninterrupted from one bow to another, the kettlehole appears in the midst of the esker chain, while the esker curves round it as a low ridge. It may be suggested that this relationship indicates that the mouth of the melt-water tunnel was plugged during the winter by a newly formed chunk of water-ice. When the tunnel was widened by melting during the succeeding summer, the chunk melted more slowly than the glacier-ice, and the water stream curved round it as indicated by the low esker ridge. The chunk of ice remained for several years and later gave rise to the kettlehole. Such a kettlehole in the first major part of each of the tunnel valleys has so far made it possible to draw a winterline west of the first of the lines already drawn (see Fig. 5).

[1] Victor Madsen, "Beskrivelse til det geologiske Kortblad Bogense: Résumé: Notice explicative de la feuille (géologique) de Bogense," *Denmark Geol. Surv.*, Vol. I, No. 7.

THE DROPPING OF THE WATER TABLE

The similarities which have been pointed out between the four tunnel valleys and the associated eskers indicate that the shape of the tunnel valleys and the eskers is the original one, and that the esker is to be regarded as a cast of the melt-water tunnel at the time when the deposition was brought to a close. The eskers were deposited near the limit between the moving and stagnant ice, sometimes reaching inside the limit, and were thus partly deposited underneath the moving ice.

The height of the eskers was primarily controlled by the amount of material carried by the stream and by the rate of widening of the tunnel. Where the deposits are undisturbed, however, the height could not exceed the level of the contemporaneous water table in the ice, and thus in the height of the deposits we have a minimum for that level. If the top of an esker is strikingly flat, we have the exact level of the water table at the point, provided the flat top is not due to later erosion and other evidence does not disprove it.

In the Naestved esker valley the steps in the dropping of the water table are noteworthy. The oldest recognized step took place when the varved clay was deposited in a lake in the Lindebjerg upland southwest of Soroe. At that time the water table here lay about 300 feet above present sea level. A younger step is represented by the melt-water deposits near Soroe, as none of them exceeds 200 feet. At this time the excavation of the Lake Tystrup basin was completed. The eskers in the western part of this valley do not rise to much more than 160 feet, and some flat-topped areas show that this elevation must be almost the level of the water table at the time of their deposition.

The eskers in the first four bows are low and comparatively small. The next important step in the dropping of the level of the water table is thus registered by the Mogenstrup esker, southeast of Naestved. The last hill in bow No. V, the second of the hills in the Mogenstrup esker proper, is clearly flat topped with the broad surface sloping northwestward, i.e., in the direction of flow of water. The height of this esker hill is almost 160 feet above sea level, indicating deposition underneath a water table at this level. The

water table sloped northwestward, dropping to only 135 feet in Lake Tystrup, where the melt water escaped through a spillway, which can be traced along a winding course northward to Stenlille (see map, Fig. 5). At the eastern end of the Mogenstrup esker, where the water escaped from the moving ice, the water table reached 180 feet. At this stage the stagnant ice spread at least to Lake Tystrup, for otherwise the melt water would have escaped to the Smaaland Sea over the lower divide southwest of the tunnel valley, as it did a year later.

The small eskers which continue the Mogenstrup esker southeastward are low and partly flat topped, showing that the water table in summer VII was only about 60 feet above present sea level. Thus it had dropped not less than 120 feet from the previous year, and this was initiated by the transformation of the ice in the Smaaland Sea into stagnant ice, probably caused by the heaping-together at that time of immense fragments of Cretaceous chalk in the eastern part of Moen. The water stream, which until now had flowed northwestward from Naestved to Lake Tystrup, was deflected to the Smaaland Sea, and at this very moment the Susaa River was born. Accordingly, the river gravels of the early Susaa River terraces rest on finer esker material, deposited by a deep, slow water stream moving up valley, as revealed by the structure of the deposits.

This dropping of the water table was greatest in this tunnel valley but was also felt in the other valleys. In the Haslev esker valley the water table at almost the same time of the year dropped at least 40 feet and the esker building was stopped for some time. On the other hand, the dropping of the water table in the two other tunnel valleys did not reach the part of the Mulstrup esker that was being built at this time 4 miles north of Haslev, and it did not affect the Koege esker valley. In summer VII the water stream which deposited the Mulstrup esker was deflected to the Koege esker stream, which still flowed through the spillway near Stenlille. A threshold south of Ringsted retarded the dropping of the water table in this valley for at least four years, until the threshold was lowered and the water could escape to the Susaa River as it does at present.

During the early stage of the Susaa River a conspicuous terrace was developed within most of its drainage system. The character of

these terraces appears to show that the foreslopes are ice-contact slopes, as there is no evidence of later erosion to an extent such that the present-day terraces can be regarded as remains of an earlier filling of the whole valley. The terraces are closely connected with the esker deposits of earlier date, and the material of which they are composed is certainly only material at hand which has been redeposited. This conception corresponds to that of R. F. Flint,[1] but while he apparently regards all the material to have been deposited during this stage, most of the material in Zealand was deposited *at* the time when the ice stagnated, and not *after* this time.

THE MORAINES AND THE WINTER LINES

A closer examination of the trend of the winter lines in their relation to the present-day physiographic features of this region appears to show that the relationship is more regular than one would expect. As to the divides it is especially interesting to note that the winter lines VII–VIII follow the present-day divide between the drainage area of the Susaa River and the area draining eastward to the sound. From a point east of Haslev to the Koege esker this line is the limit of a smooth till-plain on the west with low drumlins as long as 1–2 miles and $\frac{1}{2}$–1 mile broad, with a knob and basin terrain on the east. This difference is not related to any difference in the altitude, but is only a difference in surface form. It is due to an exceptionally strong northward pressure of the moving ice east of the line, revealed by the abrupt turn in the esker along the line. It resulted in a cracking of the ice inside the line and in a sinking of the ice blocks into the till-plain.

The drumlins west of this line are best developed in the region west of Haslev, where the ice to the southward was retarded by the Wester Egede upland. Such conditions are considered to be favorable for their development. Northwest of the upland is a large depression (the point where the name Susaa is placed on Fig. 5) in which a large body of glacier-ice was buried and remained for many years after the surrounding ice melted away. South and west of the depression is found a compound moraine ridge with the largest hills

[1] "The Stagnation and Dissipation of the Last Ice Sheet," *Geogr. Rev.*, Vol. XIX 1929; "The Glacial Geology of Connecticut: Hartford," *Conn. Geol. and Nat. Hist. Surv. Bull. 47* (1930).

orientated in a direction oblique to the northwest-southeast trend of the whole complex. The direction is used in drawing the winter lines in this hilly complex.

That these and several other morainic features were built underneath the ice is revealed by the fact that they are often covered by undisturbed glaciofluvial deposits laid down between walls of stagnant ice, and thus they themselves must have been built before the ice stagnated. The winter line found between VII and VIII crosses the Koege esker in a winter interruption, where the esker is low and small—a fact that would not be possible if the topographic differences described on the two sides of the line originated by stagnation of a receding ice front along the line.

Similar conditions appear to have prevailed in many other places in Denmark east and north of the limit of the last glaciation (Fig. 1). For deciphering the late glacial developments of these areas as well as those of other regions where eskers, drumlins, and other subglacial features dominate and no trace of a moving ice border exists, the methods of investigation described above seem particularly promising.

The region investigated appears to have been very favorable for the study of the conditions existing when the last continental ice sheet melted away from Denmark. The stagnant ice-border zone was very inactive and thus the border of the moving ice has formerly been regarded as the true ice border. That this was not the case is revealed by the eskers, the varved clay in the ice-dammed lakes, the pitted plains, and the ice-contact slopes. It is true that one must be careful in the use of stagnant ice to explain features, but in the region studied there was a very large stagnant ice-border zone at the time when the physiographic features emerged from the continental ice sheet.

The next problem will be to date exactly the ten years during which the deposition of the eskers took place, which will probably be done by means of the varves. Another problem is to continue the winter lines northward to Scania and Sweden, and southwestward to Germany, and in addition to draw older and younger winter lines wherever possible.

THE APPLICATION OF MECHANICAL STRUCTURAL PRINCIPLES IN THE WESTERN ALPS

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ABSTRACT

The writer describes briefly the most generally accepted hypothesis on the origin of the Alps, and notes that the evidence upon which this theory has been built is stratigraphic, lithologic, and paleogeographic, with almost complete neglect of mechanical structural factors. The need of employing certain mechanical structural evidence to support the other types is emphasized, and the manner of its use and application is outlined. Numerous examples are described where the writer has applied mechanical structural evidence successfully in the "Hautes Alpes Calcaires" of the western Alps. The paper urges a fuller exploitation of such evidence in attacking structural problems, and suggests that the solution of the obscure problems of Alpine structure will require its use as an important supplement to the types of evidence already used.

During the summer of 1930 the writer made a walking tour of the western Alps of Switzerland in the company of Dr. R. J. Lund, of the University of Wisconsin, and for two months studied the tectonics of that famous mountain system.[1] This study, both in the field and in the literature, was directed particularly to the theories of genesis of the structure of the Alps and to the types of evidence upon which the theories have been built. It had seemed from a general study of the literature that the mechanics of the structures had been somewhat neglected, and that some mechanical aspects had not been explained at all. The following discussion is presented primarily to point out those structural factors which do not seem to have been sufficiently emphasized, and at the same time to give a brief review of the "nappe" theory for those readers to whom it is not familiar.

THE NAPPE THEORY OF ALPINE TECTONICS

In the early years of this century M. Lugeon,[2] of the University of Lausanne, first presented his theory of the origin of the Alps, and

[1] For a comprehensive description of the entire Alps in English and a very complete bibliography of German, French, and Swiss literature on the Alps see L. W. Collet, *The Structure of the Alps*. London: Edward Arnold & Co., 1927.

[2] M. Lugeon, "Les grandes nappes de recouvrement des Alpes du Chablais et de la Suisse," *Bull. Soc. Géol. France*, 4th ser., 1901–2.

nearly all of the modifications proposed since then have been in the nature of refinements of his original theory.

For the word "nappe" there are two definitions, by authorities on its use, which have slightly different meanings. Termier[1] defines it as a "series of rock strata which is not in place, which reposes on 'substratum de hasard,' on a substratum which is not its original substratum." This does not distinguish between recumbent anticlines and thrust-faulted masses. Heim,[2] on the other hand, limits the use of the word to a thrust-faulted mass and would distinguish such masses as true nappes and refuse the term to a large recumbent anticline. Both definitions require horizontal translation of the rock mass, but Heim's insists on translation based upon a clean-cut thrust. There are other terms which have slightly varying applications, but which are essentially synonymous, such as *lambeau de recouvrement*, *lambeau de charriage*, *écaille*, and the German term *decke*, so with this disagreement of definitions one must be careful about attaching geologic significance to the word "nappe" until its actual structural significance is amplified by other information.

Perhaps the most generally accepted presentation of the nappe theory was made by Argand,[3] and it is from his work "Sur l'arc des Alpes occidentales" that the following brief sequence of events is derived. Neglecting the highly speculative stages of the embryonic geosycline, the mountain-building movement began in Middle Oligocene time (see Fig. 1).

St. Bernard phase.—A strong thrust toward the northwest started the development of the St. Bernard nappe as a very large recumbent anticline. The sediments underlying the fold were forced into a complex and similar fold which became the Simplon and Ticino nappes, and the sediments above and northwest of the Simplon-Ticino nappes responded by thrusting farther to the northwest to form the lower nappes of the Prealps. In Figure 1 the latter are found as wedge-shaped fragments in the external and internal Prealps.

Dent Blanche phase.—The Dent Blanche nappe, a true nappe

[1] P. Termier, "*Deux conférences de géologie alpine, Part II;* "La synthèse géologique des Alpes," 1910.

[2] Alb. Heim, *Geologie der Schweiz* (Leipzig, 1921).

[3] *Eclogae géol. helvet.*, Vol. XIV (1916).

whose thrust plane is immediately above the St. Bernard nappe, started to ride up over the latter. The strata overlying the Dent Blanche nappe were carried along by the movement of that nappe and separated from their roots. These upper strata, which were to become the upper nappes of the Prealps, were carried to the northwest as a passive load by the thrust of the underlying St. Bernard and Dent Blanche nappes, and then discharged in front of the nappes which had been carrying them. At the end of their journey they were deposited on top of the lower nappes of the Prealps, stretching

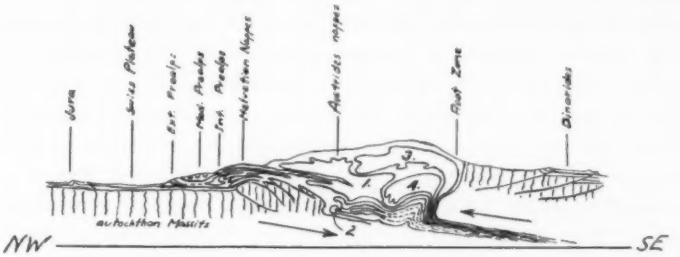

FIG. 1.—Schematic profile of the western Alps in phase Insubrienne. *1*, St. Bernard nappe; *2*, Simplon-Ticino nappes; *3*, Dent Blanche nappe; *4*, Monte Rosa nappe. (After E. Argand.)

the latter into two parts, and themselves remaining to constitute the median Prealps.

Monte Rosa phase.—At this time the Monte Rosa nappe began to develop strongly. It had its roots between those of the St. Bernard and Dent Blanche nappes, and was so closely confined that it pressed into the back of the St. Bernard nappe to produce the backward folding of that nappe as shown in Figure 1. The Simplon-Ticino nappes reached their maximum, and the Helvetian nappes began to form. The latter are a series of thrust-faulted masses whose thrusts were initiated underneath the *têtes* of the Pennine nappes. First the Wildhorn nappe was pushed to the northwest, to be followed by the Diableret nappe, and a short time later by the Morcle nappe. Each of these Helvetian nappes underlies the preceding one, and their movements resulted in the partial infolding of the overlying lower nappes of the Prealps.

Phase of Adriatic subsidence.—A period of subsidence, south of the Alps, which resulted in the roots of the Pennine nappes assuming a vertical position.

Phase insubrienne.—This is the final phase, during which the overthrust changes to an underthrust and forces the roots of the Pennine nappes to dip to the north.

DISCUSSION OF THE NAPPE THEORY

The description of the development of the nappes as given above has been purposely simplified in order to allow the reader to see the approximate relations between the different structural units. Actually, each of these units is extremely complex. For example, the lower nappes of the Prealps are grouped together as one nappe (see Fig. 2), although they consist of three separate nappes one above the other. The upper nappes of the Prealps also consist of three separate nappes one above the other and so complexly infolded that their age relations are very doubtful. Between the two there is another nappe not yet mentioned, called the Niesen nappe, which is supposed to be an extended digitation of the St. Bernard nappe. Since the source of all of these is in dispute, and promises to remain so for some time, let us examine some of the evidence which has been generally employed to reach these conclusions.

It is thought that all of the Prealpine nappes came from the southwest as great overthrusts which at one time covered the entire Alpine area, and the evidence from which this is deduced is largely paleogeographic. The facies of the Prealps do not resemble any facies found in the Helvetian nappes, nor do they resemble any in the Pennine nappes, so the Austrides, or eastern Alps, are indicated as the only possible source. Bailey Willis[1] has argued an alternative hypothesis: that the nappes of the Prealps are the remnants of an earlier thrust from the northwest followed by a thrust from the opposite direction which returned the strata to a position vertically above their original position. This would explain the absence of the roots of the upper nappes, and the superposition of older strata upon younger, but it does not seem to explain the complex infolding of a

[1] "Report on an Investigation of the Geological Structure of the Alps," *Smithsonian Misc. Coll.*, Vol. LVI, No. 31 (1912).

whole series of slices such as make up the Prealps. The Argand-Lugeon theory depends entirely on negative paleogeographic evidence of doubtful value, and Willis' theory only accounts for the raised position of one nappe, instead of six. Here is an unsolved structural problem, where the direction of differential movement between beds and between nappes would seem to be of prime importance.

Another problem in the Prealps has been that of determining the relative ages of the two upper nappes of the upper Prealps group. The Simme nappe is frequently found under the Breche nappe, which indicated to some writers that the Simme is the younger of the

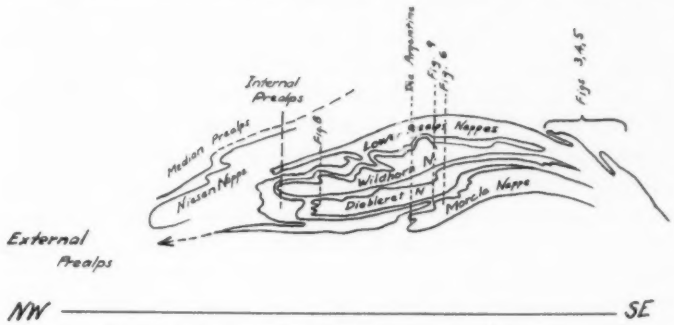

FIG. 2.—Hypothetical profile of the Helvetian nappes. (After M. Lugeon)

two. Other writers, having in mind that the lower Prealps nappes are in places found under the younger Helvetian nappes (see Fig. 2), believe that the Simme nappe is therefore older than the Breche nappe. As in the problem of locating the direction from which the Prealps nappes have come, it seems obvious that the direction of differential movement between nappes should be of great importance in determining the relative ages of these nappes.

In the Pennine nappe region there are also several interesting controversies. One of them concerns the interpretation of the structure of the Matterhorn, which is a peak carved out of the Dent Blanche nappe. The structure has been interpreted both as an anticline and as a syncline, depending upon the identification of the small pyramid which caps the mountain as being younger or older

than the underlying series. Schmidt[1] and Argand[2] have defended their respective opinions with arguments based principally upon lithologic comparisons with nearby series, and upon projections of the strata to adjacent peaks. Neither has employed structural criteria, although the problem of distinguishing an anticline from a syncline is truly structural in nature.

These controversial points, and many others, have arisen in the gradual refinement of Lugeon's theory of nappe structure and are mentioned with the intent of showing what the Alpine geologist has to face in the way of problems, and to indicate what sort of evidence he has used.

MECHANICAL STRUCTURAL EVIDENCE

The failure of a rock, when it is subjected to stress, leaves an indelible record; and when cleavage and fracture cleavage have developed as a consequence of that failure, they have written an infallible story for the geologist to read and interpret. It is this record of rock failure, expressed by flow cleavage and fracture cleavage, that is meant by the phrase "mechanical structural evidence." If a structure can be observed in its complete form, with no gaps in the continuity of formations, then no structural problem exists beyond that of accurately locating and identifying the formations, and that can be and is done upon stratigraphic and lithologic evidence. However, if gaps do exist and isolated blocks must be traced to their roots, or eroded portions of folds must be restored, then it is necessary to exploit an additional type of evidence. Under these circumstances the discovery of flow or fracture cleavage in a rock should have the same significance to the solution of the problem as the discovery of a key fossil would have in working out a stratigraphic succession. In the western Alps the identification and mapping of observed rocks has been largely finished; the reconstruction of what erosion has destroyed and the interpretation of hidden structures is still uncompleted, and may remain uncompleted unless mechanical structural evidence is added to the other types of evidence and properly interpreted.

[1] C. Schmidt, "Ueber die Geologie des Simplongebietes," *Eclogae géol. helv.*, Vol. IX (1907).

[2] E. Argand, "L'exploration géologique des Alpes Pennines centrales," *Bull. des Lab. Géol. Géog. Phys. Min. et Paléont. de l'Université de Lausanne*, 1909.

Consider the simple example of two adjacent limbs of the same formation standing vertically; their lower projections covered with soil or talus, and their upper projections destroyed by erosion. If one is able to determine the tops and bottoms of the beds by means of ripple marks, cross bedding, or gradations in size of grain, the structure can be interpreted easily. Usually, however, these criteria are not available, and particularly is this so when the rocks have been badly sheared. Under these circumstances the easiest way to determine the structure is to apply the principles derived from the relations between cleavage and bedding. If the cleavage indicates that the inner beds have moved upward relative to the outer beds, the structure is synclinal; if the outer beds have moved upward relative to the inner beds, the structure is anticlinal.

The Helvetian nappes of the Hautes Alpes Calcaires (see Fig. 2) are probably the best-exposed structures in the western Alps, and there the writer observed numerous examples of mechanical structural evidence where direct corroboration of what that evidence implied could be seen. The following paragraphs are devoted to a few of these examples which show how the broad structural features of the western Alps are reflected by the minor details.

The accompanying Figures 3, 4, and 5 are of outcrops observed in the root zone of the Helvetian nappes, and their approximate location is marked upon Figure 2. Figure 3, a sketch made in the Sanetch Pass about one kilometer north of the village of Chandolin, shows a bed of limestone between two beds of black calcareous schist. The beds dip about 68° to the southeast, and it will be noticed that the cleavage in the schist dips only about 45°. The limestone itself exhibits well-developed fracture cleavage, S-shaped, and inclined at a still flatter angle. By using the well-established principle that flow cleavage indicates approximately the direction of maximum elongation, the axial plane of the fold must dip about 45° to the southeast. The two planes of maximum shear are expressed in the competent limestone, one by the bedding and the other by the frac-

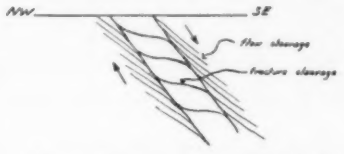

FIG. 3.—Overturned limb in the Root Zone of the Wildhorn nappe.

ture cleavage. The inferences which can be drawn are clear: first, that the beds are overturned, because the differential movement between beds indicates that the anticline is southeast of this exposure; second, that the axial plane of the original fold was inclined 45° to the southeast. The latter inference must be limited in application because of the effect of subsequent movements. Figures 4 and 5 are photographs taken in the gorge of the Lizerne River, a few miles west of the location of the outcrop sketched in Figure 3, and still in the root zone shown on Figure 2. Here the bedding is inclined only

FIG. 4.—Cleavage in the Root Zone of the Diableret nappe

15° to the southeast; the cleavage is inclined about 65° in the same direction; and the fracture cleavage in the limestone (Fig. 4) is almost vertical, or perhaps dipping 85° to the northwest. A theoretical strain ellipsoid applied to this exposure would show a maximum elongation inclined about 65° to the southeast and the two planes of maximum shear again expressed by the bedding and the fracture cleavage. However, in this case the beds are right side up, and the upper beds have moved upward relative to the lower beds in the proper differential movement between beds in the normal limb of an anticline. Figure 5 was taken only a few feet away from Figure 4

along the same beds, and shows how a slight difference in composition, or competency, in the limestone member has allowed the development of flow cleavage in it instead of fracture cleavage. These observations, the first from the root zone of the Wildhorn nappe and the next two from the root zone of the Diableret nappe, could be of some value eventually in reconstructing each stage in the development of the nappes. If it is possible to determine the attitude of the axial plane of each of these nappes now, it should be possible by careful searching for similar exposures to straighten out the folded thrust planes and to reestablish the position of each recumbent fold before it sheared. Furthermore, it is quite easy to identify those beds which are overturned and those which are normal by the use of cleavage alone.

FIG. 5.—Cleavage in the Root Zone of the Diableret nappe.

Figure 6 is a photograph taken immediately south of Anzeindaz where the nose of the Morcle nappe is beveled by erosion (its approximate location is indicated on Fig. 2). The beds are dipping gently to the north, and the fold plunges gently to the northeast. The well-developed flow cleavage is horizontal, and the fact that this cleavage is considerably inclined to the bedding would suggest that the nose of the fold is not far away. In Figure 7, a photograph of the north face of the Argentine, we see the actual nose of the fold, and a bedding surface is exposed. A close examination of the vertical

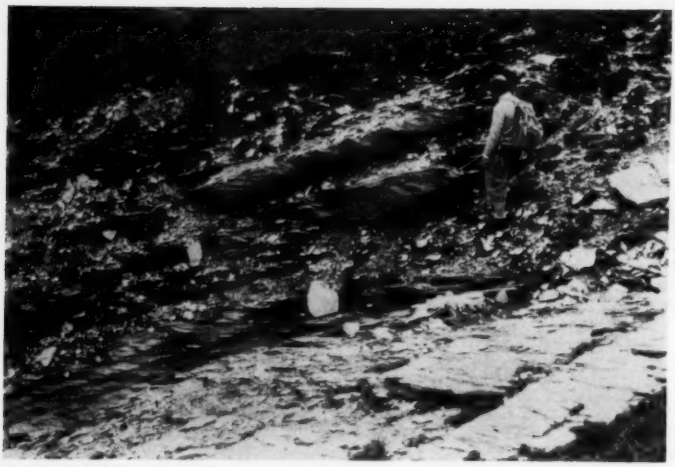

FIG. 6.—Cleavage in the Morcle nappe south of Anzeindaz

FIG. 7.—The north face of the Argentine

beds in the face of the Argentine shows the cleavage in the same attitude as in Figure 6, horizontal and approximately normal to the bedding. In Figure 8 cleavage is shown normal to the beds in a synclinal digitation of the overlying Diableret nappe, near Taveyannaz (see Fig. 2 for its approximate location). Farther to the east at Derborence an inner nose of the Morcle nappe in relatively the same position as the face of the Argentine again shows flow cleavage almost normal to the bedding. Figure 9 is a slightly idealized sketch of this exposure, made to show the trace of the cleavage on the bedding surface. The trace of the cleavage on the bedding measures the pitch of the fold, and, as this sketch shows, the Morcle nappe is plunging to the east where only a few miles away it disappears beneath the Diableret nappe. The cleavage is slightly inclined to the southeast, and the axial plane of this inner bed of the Morcle nappe is intermediate in inclination between the axial plane observed in the root zone and that observed in the outer nose. As in the cases in the root zone, inferences concerning the inclination of the axial planes of nappes must be accepted only tentatively until further observations have enabled the geologist to discover how much the original inclinations have been modified by subsequent movements.

FIG. 8.—Cleavage in a synclinal digitation of the Diableret nappe.

FIG. 9.—Cleavage in an inner nose of the Morcle nappe.

From the valley of Salenfe, lying between the Luisin and the Dents du Midi, the nappe de Morcle is shown in cross section (Fig. 10). This section is some distance west of the section described in Figure 2, and the upper Helvetian nappes have been completely removed by erosion. The Tour Sallière is formed by the Jurassic core of a recumbent anticline, with Cretaceous and Tertiary strata at its base representing the reversed limb of the envelope. Below the reversed limb there is a thin layer of autochthonous Triassic, and below that the crystalline basement belonging to the Aiguilles Rouges massif. Immediately north of the Tour Sallière are the peaks of the Dents du Midi, composed of Cretaceous strata; the Cretaceous envelope has been pushed beyond the core at the crest of the anticline. The cross section is important for several conclusions

FIG. 10.—Section across the Morcle nappe. *1*, Aiguille Rouge crystallines; *2*, Porphyry; *3*, Autochthon; *4*, Tertiary; *5*, Cretaceous; *6*, Jurassic; *7*, Gneissic Mylonites. (Simplified after Schardt, Collet, De Loys, and Gagnebin.)

which may be drawn from it. The Jurassic beds which form the core of the recumbent fold are now nearly horizontal, but since the surface of the autochthonous basement upon which they lie dips about 20° to the north, it seems probable that there has been thrusting and tilting of the basement since the formation of the nappe. In other words, the maximum elongation, of which the original asymmetric fold was an expression, was not as low angled as might be supposed from the present attitude of the nappe. The importance of this observation lies in its apparent agreement with the results of previously noted observations of the axial planes of the higher Helvetian nappes within their root zones. In every case the axial planes of the nappes have been well inclined, from 20° in the nappe de Morcle to 65° in the nappe de Wildhorn, and yet in all cases the *têtes* are now lying nearly horizontal, or in some cases pitching to the north. It seems to be a fair inference that all of the thrust planes, or axial planes of folds as the case may be, at one time dipped considerably to the

south, the latter more than the former. Each thrust plane has been distorted by the subsequent nappes, and finally all of them have been moved by the thrusting and tilting of the Hercynian basement. In order to determine just how much actual horizontal translation there was in these Helvetian nappes we must attempt to work back through the accumulated movements by means of the sort of evidence here described.

In the development of the Morcle nappe the first step was the formation of a simple asymmetric fold, inclined about 20° to the south, with its outer beds of Cretaceous pushed away from the core at the crest of the anticline. Then the reversed limb sheared and the fold became a true nappe. The thrust was carried by the upper limb

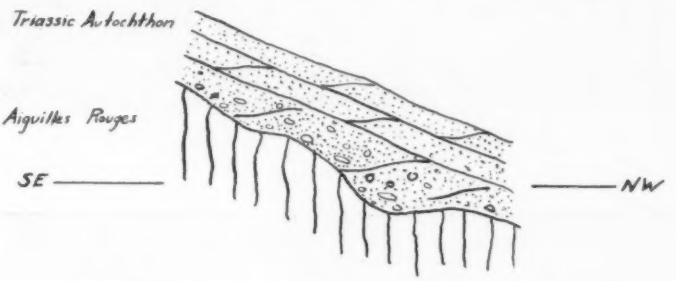

FIG. 11.—Fracture cleavage in the Autochthon below Tour Sallière

of Cretaceous and by the Jurassic core, but the reversed limb of Cretaceous and some Tertiary became a passive member squeezed between the overlying core and the underlying autochthon and Hercynian massif. Finally the Hercynian basement was thrust and tilted to the north so that the nappe assumed a nearly horizontal position. This sequence of events can be very closely determined by an examination of cleavage in various strata in the east face of the Tour Sallière. At the base of the mountain the thin autochthonous beds have developed rather rough fracture cleavage (Fig. 11) *since* the shearing of the reversed limb. The next strata above, belonging to the reversed limb of the envelope of the nappe, show fracture cleavage of the same sort, better developed (Fig. 12). It is quite obvious from the direction of differential movement indicated in these two exposures that the fracture cleavage in both of these mem-

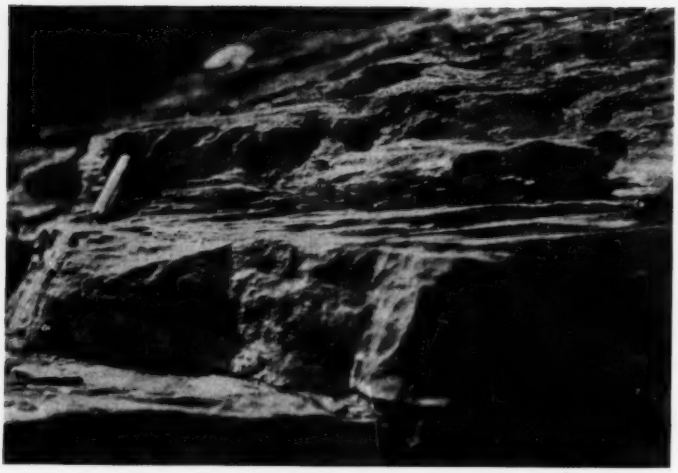

FIG. 12.—Fracture cleavage in the reversed Cretaceous limb—Tour Sallière

FIG. 13.—Fracture cleavage in the Jurassic core—Tour Sallière

bers was developed by the drag of the overlying nappe subsequent to the shearing of the reversed limb of the fold, and not during the folding. They behaved as passive members between the moving mass of the nappe and the Hercynian massif. The lower strata of the Jurassic core of the Tour Sallière, found higher on the face, exhibit fracture cleavage inclined in the opposite direction (Figs. 13 and 14); that is, the cleavage indicates that the lower beds have been thrust northward under the upper beds by the normal differential movement between beds in an anticline. This cleavage is earlier than that seen in Figures 11 and 12, and clearly was developed during folding. The absence of an older cleavage with similar inclination in the reversed limb of Cretaceous probably shows that the Cretaceous acted as a competent member during the folding, and only yielded to subsequent shearing when it became a passive member between the nappe and the basement.

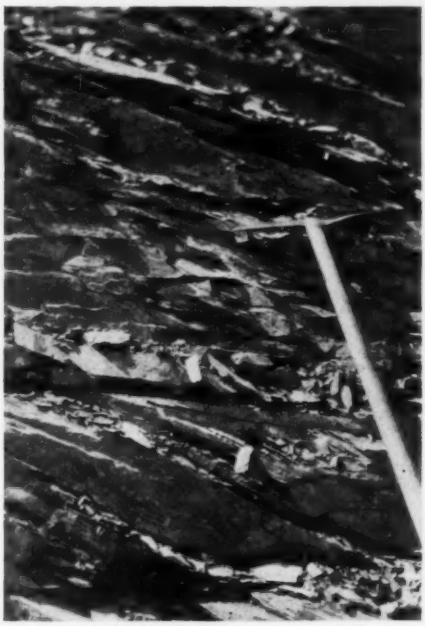

FIG. 14.—Fracture cleavage in the Jurassic core —Tour Sallière.

There are additional structural criteria which perhaps deserve more emphasis than they have had, namely, the various methods of determining tops and bottoms of beds. In a few places, notably in the autochthon below the Tour Sallière, ripple marks are well developed (see Fig. 15). In the Diableret nappe one exposure of Taveyannaz grés on the north slope of the Roches de Vent contains several beds from one to two inches thick in which the sand grains show a remarkable gradation in size of grain from coarse at the bot-

tom to very fine at the top. There are no contradictions or any doubtful lines of demarcation between beds. In the same exposure there are many splendid examples of cross bedding, all of which indicate the tops and bottoms surely.

FIG. 15.—Ripple marks in the Autochthon below Tour Sallière

CONCLUSION

These few examples of the use of mechanical structural criteria to supplement other sources of information show that even in the Helvetian nappes, which are comparatively well known, additional knowledge can be easily gained. It is, perhaps, not so certain that similar structural evidence can be applied to the more obscure parts of the Alps, but there is no apparent reason why it may not. The controversy between Argand and Schmidt over the proper interpretation of the structure of the Matterhorn, for example, might have been settled very easily by structural evidence alone. The differential movements between beds in an anticlinal structure are exactly opposite to the same movements in a synclinal structure, and provided cleavage has been developed, the question might have been settled by these criteria without calling on lithologic similarities or geometrical projections at all. The problems of the Prealps are not so simply solved, because there the rocks have been sheared so often, and are so incompetent, that satisfactory evidence is difficult to find. However, we may discover that, in spite of these obstacles, mechanical structural evidence is as reliable as any.

SOLUTION DEPRESSIONS IN SANDY SEDIMENTS OF THE COASTAL PLAIN IN SOUTH CAROLINA

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ABSTRACT

Numerous depressions occur near the inner margin of the Coastal Plain of South Carolina. They are not due to wind action or to any of the other common causes of depressions. Evidence is presented to show that they are a result of solution of iron and aluminum from sandy sediments by ground water. The solution is effected by organic acids resulting from decay of vegetation. Once started, solution is accelerated by increased dampness, and increased growth of vegetation.

LOCATION

Shallow depressions are common along the inner margin of the Coastal Plain of South Carolina. They are abundant in the Sand Hill belt which forms a broken fringe along the Fall Line throughout its extent in a southwesterly direction across the state. They also occur elsewhere in this same general region in areas less sandy and less hilly than the typical Sand Hills. Where most numerous, there may be as many as four or five well-defined depressions per square mile.

CHARACTER OF THE ROCKS

The rocks of this region are of Cretaceous and Tertiary age. They consist of clayey, red, buff, white, and mottled sands. In the typical Sand Hills there is very little clayey matter between the sand grains. These materials are commonly cross bedded. A bed of gravel, several feet in thickness, is often found either interstratified with the sediments or underneath them at their contact with the underlying crystalline rocks. Ferruginous deposits frequently occur immediately above the denser impervious clay beds.

DESCRIPTION OF THE DEPRESSIONS

The depressions are found chiefly on the summits of flat-topped divides. Many are shown on the topographic maps of the Aiken and Warrenville, South Carolina, quadrangles (see Fig. 1). The surrounding topography may be gently rolling to knobby; but more

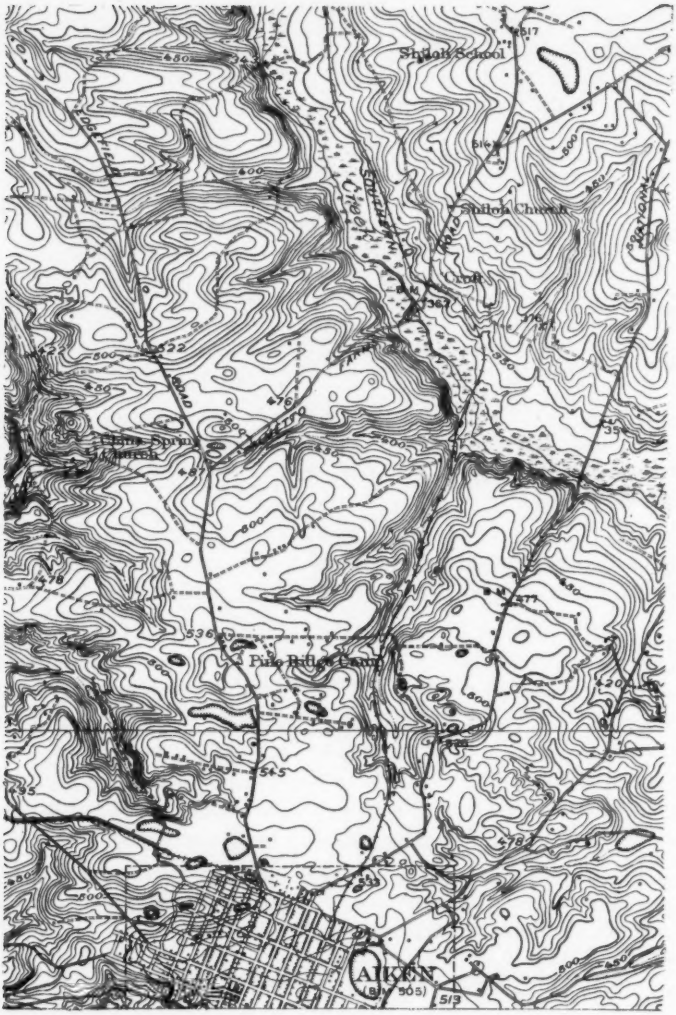

FIG. 1.—Depressions: A portion of the Aiken, S.C., topographic map, U.S. Geol. Surv. Scale, 1 mi. = 1 in. Contour interval, 10 ft.

frequently the depression is the only feature breaking an otherwise monotonously flat surface. In rare instances depressions occur on the slopes of divides (see Fig. 2). In practically every case a well-defined and usually steep-sided valley can be found at no great distance from the depression.

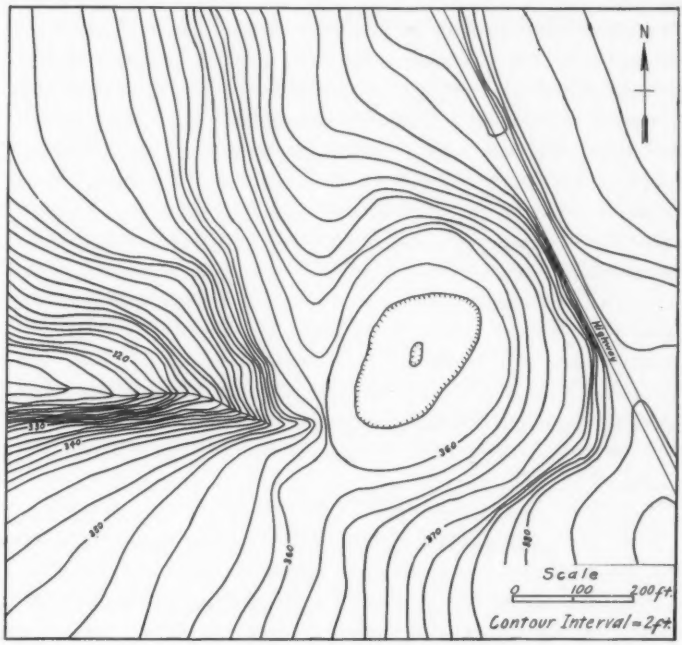

FIG. 2.—Depression five miles north of Columbia, S.C.

In size the depressions range from a hundred yards to $\frac{1}{2}$ mile in diameter. The median is about 250 yards measured from the summit of the rim to a corresponding point on the opposite side. In depth they vary from 4 to 20 feet, measured from the lowest point on the surrounding rim to the lowest point in the depression. The average depth is about 8 feet.

Most of the depressions are nearly circular in shape, much more so than those shown in Figure 1; some are oval shaped; only a few

have irregular outlines. They are similar in shape to depressions resulting from the solution of limestone, though in general they are more symmetrical.

Some of the depressions contain water; others have been drained by means of ditches. In most cases drainage is easy because of proximity to deep-cut valleys. The shallower ones are dry, but even these show evidence of once having contained water. The soil near the center for a foot or less in depth is dark colored because of the presence of partly decayed vegetable matter. Where much dark soil is present it invariably contains large quantities of the spicules of fresh-water sponges. Living fresh-water sponges have been found in the ponds occupying depressions in the vicinity of Columbia, South Carolina. The presence of such large quantities of sponge spicules in soils from the centers of the depressions now dry shows that they once contained water.

The little siliceous spicules are a source of much discomfort to those who till the rich soil in the bottoms of these depressions. The sharp points cause an irritation of the skin which is locally called "the itch." Professor J. T. Penny, of the University of South Carolina has identified several species of the sponges, among the most common of which are *Tubella pennsylvanica* and *Heteromyenia ryderi*.

ORIGIN OF DEPRESSIONS

None of the usual explanations of the origin of depressions seems to apply to these. Obviously they cannot be due to glaciation.

Neither are they due to solution of limestone. Similar depressions formed by the solution of marls are common lower down in the Coastal Plain, as, for example, near Eutaw Springs and Ferguson in Orangeburg County, and are shown in great number on the Eutawville topographic quadrangle. But no marls are found in the Sand Hill belt. Numerous wells have been driven in the vicinity of Aiken and Camden, and elsewhere along the inner margin of the Coastal Plain in South Carolina, many penetrating to the underlying crystalline rocks, but in no instance has limestone rock of any sort been encountered. Careful search of outcrops in this region has also revealed no trace of a lime rock.

It has been generally assumed that the depressions in the Sand

Hill belt may be due to wind action. Possibly some may be due to this cause, but the facts indicate that the great majority of them are not. Most of them occur where the land is otherwise perfectly flat. If they are due to wind one would expect to find nearby dunes or mounds of sand accumulated from material blown out of the depressions. Many depressions occur in materials that are either too clayey or too coarse to have been shifted about by wind. Two depressions studied in detail occur in sediments in which about one third of the fragments range from $\frac{1}{4}$ to over 1 inch in diameter. They could not have been formed by wind action while containing water. The presence of dark soil and sponge spicules shows that all of them once contained water and that they have not suffered any deepening by wind action since becoming dry. They must be recent in origin and due to some process operating at present for soil wash is rapid on sandy slopes, tending to fill up depressions in time. The remarkably symmetrical outline of these depressions is also evidence against the wind-action theory.

THEORY OF ORIGIN OF DEPRESSIONS IN SANDY SEDIMENTS

Recent investigations by the writer have led him to the conclusion that the depressions have been formed by leaching of the sediments. The leaching is locally accelerated by acids resulting from the decay of vegetation. Such acids are effective solvents for iron, aluminum, and the other basic constituents of the clayey sands. The solution and leaching out of 8 per cent of the soluble matter in any one place from 100 feet of sediments would result in the formation of a depression 8 feet in depth, assuming that the loss is volumetric. Slight depressions may have existed since the uplift of the Coastal Plain, or they may have resulted from the uprooting of trees, etc. In such slight hollows the vegetation would grow ranker than elsewhere, because of greater moisture. The greater abundance of vegetation would, upon decay, increase the supply of acids, and leaching of the underlying sediments would become more active. Thus an originally slight depression or hollow would tend to become deeper, and the process of downward leaching by ground water accelerated up to a certain point.

SAMPLING AND ANALYSIS OF MATERIALS

If the depressions are due to leaching of the more soluble constituents of the sediments, then the sands beneath the centers of the depressions should have a different composition from sands around the rims. Of course if all the constituents were leached out in the same proportion, the composition of the sands would undergo no change, and it would be difficult to prove that leaching had occurred.

In order to test this hypothesis, holes were drilled in the centers and around the rims of the depressions with a $1\frac{1}{2}$-inch augur drill, and samples were taken every 2 feet in depth. An attempt was made to drill all holes to a depth of 12 feet, but often this was not possible. In some places the drill encountered beds too sandy to be picked up by it and in others gravel or ferruginous layers too hard to be penetrated by it.

After a number of analyses were made it was found inadvisable to take samples at shallower depths than 4 feet since the sediments are everywhere leached to some extent near the surface. A ferruginous zone was often encountered at the level of the water table except in the centers. The samples taken from holes in the centers also lacked the buff and red colors of the normal sediments, thus suggesting that the iron had been largely leached out or at least had been reduced to the ferrous state. Holes were drilled in the centers and around the rims of five depressions, and nearly two hundred analyses were made for the percentage of iron and total soluble matter. The results of these analyses are shown in Table I. In every case the percentage of iron in samples from holes drilled in the centers of depressions was much less than the percentage of iron in samples from holes drilled around the rims. The average content of iron of all samples from holes in the centers was 0.77 per cent; the average content of iron of all samples from holes drilled around the rims was 2.87 per cent, a difference of 2.10 per cent.

These results were so encouraging that analyses of the samples were made for total soluble matter. During the latter part of the work this was the only analysis made. For this analysis the samples were pulverized in a mortar. A 10-gm. portion was digested for ten

TABLE I

ANALYSES OF SOIL SAMPLES FROM DEPRESSIONS

Depression No.	Depth in Feet	Center of Depression				Rim of Depression			
		Per Cent Iron		Per Cent Total Soluble Matter		Per Cent Iron		Per Cent Total Soluble Matter	
		Hole No. 1	Hole No. 2	Hole No. 1	Hole No. 2	Hole No. 1	Hole No. 2	Hole No. 1	Hole No. 2
1	4	0.54	.....	17.72	23.75	1.97	2.06	24.95	36.25
	6	.65	.....	14.55	20.05	4.50	1.61	34.45	30.15
	8	.27	.....	13.90	14.25	3.42	1.79	29.50	21.00
	10	.70	.....	13.65	8.40	2.45	0.94	35.20	20.55
	12	0.72	.....	23.50	12.85	.....	0.70	.....	15.85
Average per cent		0.58		16.26		2.25		27.89	
2	4	0.76	.....	16.25	11.60	4.56	.....	27.85	22.40
	6	1.85	.....	26.95	20.80	4.88	.....	29.20	25.90
	8	0.94	.....	22.60	13.40	1.85	.....	21.25	24.75
	10	1.08	.....	22.20	24.85	1.79	.....	21.10	18.05
	12	0.88	.....	19.00	.....	1.53	.....	17.10	14.70
Average per cent		1.10		19.53		2.92		22.23	
3	4	0.43	.....	10.40	.....	.....	.....	.....	.....
	6	.60	.....	26.05	.....	1.53	.....	19.10	.....
	8	.54	.....	12.30	.....	1.67	.....	27.10	.....
	10	.73	.....	18.75	.....	2.23	.....	33.30	.....
	12	0.54	.....	10.30	.....	2.23	.....	30.75	.....
Average per cent		0.56		15.56		1.92		26.81	
4	4	.....	.....	11.45	10.96	.....	.....	24.87	18.04
	6	.....	.....	12.27	12.84	.....	.....	30.17	27.38
	8	.....	.....	.....	.....	.....	.....	.....	16.76
Average per cent		.....		11.88				23.44	
5	4	0.66	0.98	.....	17.10	3.86	5.85	28.80	40.00
	6	0.48	1.79	10.35	19.05	5.65	5.28	51.00	33.75
	8	.....	0.60	.....	8.00	3.59	.....	31.25	.....
	10	.....	0.48	.....	12.04	.....	.....	.....	.....
Average per cent		0.83		13.31		4.37		36.97	

No. 1. Depression in Oakwood section of east Columbia.
No. 2. Depression in Rose Hill section of east Columbia.
No. 3. Depression on Sumter road 8 Miles east of Columbia.
No. 4. Depression on Monticello road 5 Miles north of Columbia.
No. 5. Depression ½ Mile West of Ridge Springs, S.C.

hours over a water bath with 100 cc. of 6 N hydrochloric acid. At the end of this period the samples were filtered into a 250-cc. volumetric flask and a 50-cc. aliquot part was evaporated to dryness and weighed. The total average soluble matter for all the samples from holes drilled around the rims of the depressions was 24.47 per cent. The total average soluble matter for all the samples from holes drilled in the centers was 15.31 per cent, making a difference of 12.16 per cent.

The accordance in the results of analyses from all the depressions studied is remarkable, considering the difficulty of obtaining fair samples. These analyses show clearly that a large percentage of certain constituents has been leached from the sediments immediately under the depressions. Analyses of the filtrates from the hydrochloric acid digestion were made in order to determine what elements had been leached out. The results are shown in Table II.

TABLE II

	Per Cent
Silicon, calculated as silicic acid	1.30
Iron, calculated as ferric chloride	14.00
Aluminum, calculated as aluminum chloride	81.00
Calcium, calculated as calcium chloride	1.60
Magnesium, calculated as magnesium chloride	0.70
Alkalies, calculated as sodium and potassium chlorides in equal proportions	1.00

If the foregoing are the constituents of the filtrate resulting from the hydrochloric acid digestion, then the differences in the total soluble matter between the rims and the centers must be due to differences in the percentages of the foregoing elements. Iron and aluminum constitute 95 per cent of the dissolved matter. These are the principal elements leached from the centers of the depressions by groundwaters charged with organic acids. In the lean soils of this region little else can be dissolved by these waters. Undoubtedly the iron is present principally in the form of ferric oxide and the aluminum in the form of hydrous silicates.

An attempt was made to duplicate conditions prevailing in the field and to determine the leaching power of waters containing organic acids. Humus from one of the depressions was mixed with distilled water; after standing three days the solution was filtered

off. This solution was slightly acid, the pH being 6.7. Ten pounds of typical soil were stirred into two quarts of the solution. After standing ten days the liquid was filtered off, evaporated, and the amount of dissolved solids determined. It was found that the gain in weight was .02 gm. per 100 cc. of water.

STRUCTURE OF THE DEPRESSIONS

Few good exposures of the contact of sediments and crystalline rocks occur in the near vicinity of the depressions, but where found the contact is very undulating. A bed of quartz conglomerate commonly lies at the base of the sediments. This conglomerate varies from a foot to 8 or 10 feet in thickness. The individual pebbles average about $1\frac{1}{2}$ inches in diameter.

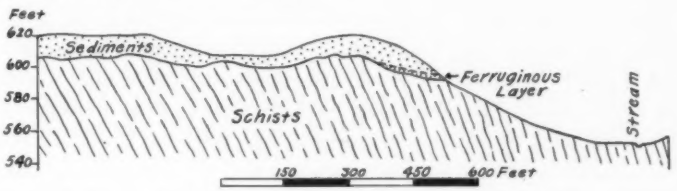

FIG. 3.—Depression one-half mile west of Ridge Springs, S.C.

In depression No. 4 (see Fig. 1), located 5 miles north of Columbia, a coarse conglomerate was struck in the center at a depth of 6 feet. It was also encountered at the same elevations in holes drilled around the rim, and was found outcropping in the vicinity of the depression. Another bed of conglomerate is found at the base of the sediments about 25 feet below the upper bed. These conglomerates afford good drainage and thus aid in the formation of the depressions.

The structure of a typical depression is shown in the cross section (Fig. 3). This is depression No. 5, located $\frac{1}{2}$ mile west of Ridge Springs, South Carolina. It is 12 feet in depth measured from the lowest point on the rim, and is remarkable in that the sediments here have a maximum thickness of less than 30 feet. In the center the underlying schists were encountered after drilling through only 3–7 feet of sands. In a cut along a nearby highway where the contact is well exposed for a hundred yards there is a bed of highly ferruginous coarse sandstone, 3 or 4 feet thick, at the base of the

sediments. Three holes drilled near the center of the depression were continued downward into the underlying decomposed crystalline rocks, but in none of these was the ferruginous layer encountered at the base of the sediments.

The sandy sediments around this depression are especially coarse, containing a high percentage of pebble-like concretions, from ½ to 2 inches in diameter. These pebbles consist of sand grains cemented together by iron; and a high iron content is also indicated by the red color of the sediments. The ferruginous layer at the base of the sediments is due to the leaching of iron from the overlying beds and its redeposition on the relatively impermeable schist. The absence of the iron deposit beneath the depression is due to the solvent action of the acid-charged ground water.

The question arises, "How can a depression 12 feet deep be formed by leaching of iron and aluminum from sediments not more than 30 feet thick?" The analyses of the underlying decayed schists furnish the explanation. The crystalline rocks are weathered to clays for some distance beneath their surface. Samples of these decayed schists from beneath the depression show much less iron and total soluble matter than samples of the decayed schists from holes around the rim. In hole No. 2 on the rim the schist was encountered at a depth of only 3 feet. It was thoroughly weathered into a buff to deep-red clay that showed little evidence of leaching. At a depth of 4 feet the iron content was 5.85 per cent and the total soluble matter was 40 per cent. At a depth of 6 feet the iron content was 5.85 per cent and the total soluble matter was 33.75 per cent.

Hole No. 1 near the center struck the decayed schist at a depth of 3½ feet. At a depth of 4 feet the iron content was 0.66 per cent and the total soluble matter 10.35 per cent. At a depth of 6 feet the iron content was 0.48. Hole No. 2 near the center struck decayed schist at a depth of 7 feet. At a depth of 8 feet the iron content was 0.60 per cent, and the total soluble matter was 8.00 per cent. At a depth of 10 feet the iron content was 0.48 per cent and the total soluble matter was 12.04 per cent. The average of six analyses of samples from within the depression when compared with the average of five analyses of samples taken around the rim shows 5.04 per cent less iron and 28.74 per cent less total soluble matter.

Undoubtedly this difference in content of iron and total soluble matter is due to the leaching of the schists beneath the depression, which has probably been facilitated by joints in the schist and nearness to a deep valley affording good underground drainage.

FACTORS FAVORING THE FORMATION OF SOLUTION DEPRESSIONS IN SANDY SEDIMENTS

It has long been known that considerable leaching of basic constituents has occurred in sandy materials of the southern Coastal Plain. Striking evidence of this is seen in the layers of limonite commonly found immediately above impervious beds of clay. The presence of such ferruginous layers above the kaolin beds is of assistance in locating these deposits.

Additional evidence of rapid leaching of iron is found in the limonite crusts which form in drainage ditches, stream beds, and gutters along highways. Many of the depressions have been drained by ditches, and along the sides and bottoms of these ditches deposits of limonite are almost invariably found. The deposits may be several inches thick, especially if the ditches have been in existence for several years.

The factors favoring the development of solution depressions in sandy sediments are as follows:

1. Porosity and permeability facilitate seepage and thereby increase the solution of the rocks by groundwater. All the depressions occur in sandy materials, and many of them are known to be underlaid by gravel beds.

2. Flat land reduces the run-off and therefore increases leaching. Practically all the depressions are located on flat-topped divides. The few depressions found on slopes may be explained by the occurrence of thick porous beds below the surface, which afford unusually good underground drainage.

3. Deep-cut valleys in the vicinity of the flat areas accelerate underground drainage and therefore leaching.

4. Abundant rainfall is necessary for vegetation and for the formation of organic acids as well as for the solution of mineral matter.

5. A warm moist climate hastens plant growth and promotes decay and leaching. In cold regions the freezing of the ground tends to

check underground drainage. Alternate freezing and thawing accelerates slope wash and the filling of depressions.

Careful examination of the topographic maps that have been published reveals no depressions in the Coastal Plain outside of South Carolina. This may be due to the large contour interval used and lack of accuracy in mapping, for it is to be expected that solution depressions in sandy sediments occur in other regions where the conditions are favorable.

RECENT STREAM INTERCISION

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Although the change in outlet of a river into a lake or sea by means of recession of the shore is a recognized phenomenon, it is rare that a geologist has an opportunity to see this process in operation.[1]

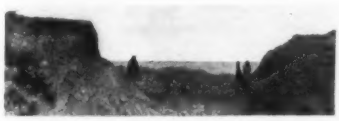

FIG. 1.—The first breach had been produced by a meander scar, June 27, 1925. Photo by F. T. Thwaites.

FIG. 3.—In 1928 the creek was the active agent, May 19, 1928. Photo by F. T. Thwaites.

FIG. 2.—In 1927 the creek was the active agent, May 20, 1927. Photo by F. T. Thwaites.

FIG. 4.—In 1929 the waves undermined the lake cliff, May 26, 1929. Photo by F. T. Thwaites.

On May 3, 1925, the writer first visited the exposure of the interglacial forest bed at Two Creeks, in Sec. 11, T. 21 N., R. 24 E., Manitowoc county, Wisconsin. The lake cliff in this vicinity is between 15 and 20 feet in height and is composed of clay. On that day

[1] I. A. Lapham, "On the Existence of Certain Lacustrine Deposits in the Vicinity of the Great Lakes, Usually Confounded with the 'Drift,'" *Amer. Jour. Sci.*, Vol. III (1847), p. 92; T. C. Chamberlin, "Geology of Eastern Wisconsin," *Geol. of Wis.*, Vol. II (1877), p. 130; J. W. Goldthwait, "The Abandoned Shore-lines of Eastern Wisconsin," *Wis. Geol. and Nat. Hist. Surv. Bull. 17* (1907), pp. 48–50; J. W. Goldthwait, "Intercision, a Peculiar Kind of Modification of Drainage," *School Sci. and Math.*, Vol. VIII (1908), pp. 129–39; Lawrence Martin, "The Physical Geography of Wisconsin," *Wis. Geol. and Nat. Hist. Surv. Bull. 36* (1916), pp. 273–74, 289; W. C. Alden, "The Quaternary Geology of Southeastern Wisconsin," *U.S. Geol. Surv. Prof. Paper, 106* (1918), p. 340; J. R. Ball, "The Intercision of Pike River, Near Kenosha, Wisconsin," *Ill. State Acad. Sci. Trans.*, Vol. XIII (1920), pp. 323–26.

the impending intercision was noticed as a small breach which had been produced by a meander scar of a small wet-weather creek (Fig. 1). As the level of Lake Michigan between May, 1925, and May, 1928, ranged between 578 and 580.81 feet, the creek was the active agent (Figs. 2 and 3), for the waves rarely reached the cliff. In May, 1929, the lake level rose to 582.9 feet,[1] the waves under-

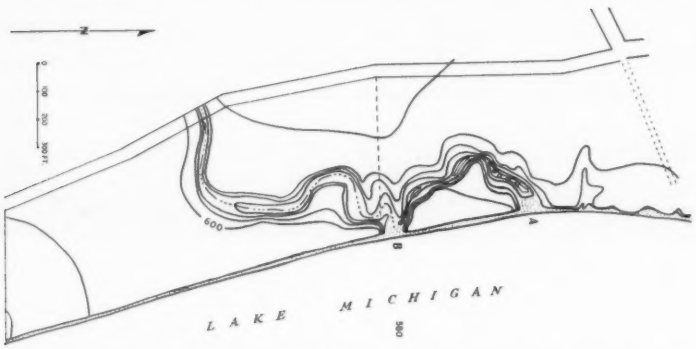

FIG. 5.—Contour map of shore of Lake Michigan just south of Two Creeks, Wisconsin. As a result of undercutting by the creek on the one side and the waves on the other, the creek now enters the lake at *B* instead of *A*. Surveyed by F. T. Thwaites, September 20, 1930.

mined the cliff and removed the barrier between the creek and the lake (Fig. 4). As a consequence, the creek now enters the lake approximately 500 feet farther south. The exact date of this event was not ascertained from eye witnesses, but as the Weather Bureau at Green Bay, Wisconsin, reports strong northeast winds on March 31, April 1, and April 5, 1929, it is fair to presume that the intercision took place on one of these dates. Since 1929, no marked change has occurred at the new outlet, as the lake level has been falling. The map (Fig. 5) was surveyed by F. T. Thwaites on September 20, 1930.

[1] Personal communication, United States Lake Survey Office, Detroit, Michigan.

"SEINE" OR "COUTCHICHING" BY J. E. HAWLEY: A DISCUSSION

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DISCUSSION BY JAMES E. GILL

The structural relations and age of the belt of schistose sediments extending eastward from Rainy Lake have been discussed recently by J. E. Hawley,[1] who has studied with particular care a limited part of the belt in the vicinity of Steep Rock Lake. Hawley's field data provides the basis for a new hypothesis which he advances to explain the origin of the structures in the district and which, he concludes, supports the view that the series in question is post-Keewatin in age. In the present writer's opinion, certain of Hawley's structural interpretations are in conflict with this conclusion concerning the age of the sediments. Also, the main hypothesis of origin, while interesting, presents grave mechanical difficulties and is opposed to certain established facts of geological history in the region. In view of the importance of the relations involved, these points are discussed at some length below.

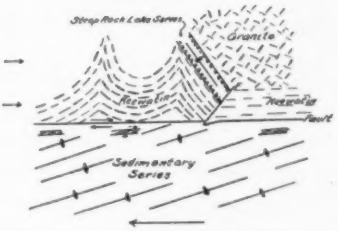

FIG. 1.—Diagram illustrating the manner in which the north-south folding of the Keewatin and Steep Rock Lake series may have been brought about by the same forces producing the easterly folding and faulting of the Southern Sedimentary series. The angle made by the axes of the folds and the contact fault is exaggerated. (Reproduction of Fig. 7 and caption in Hawley's paper.)

The distribution of the rocks in the district is shown in Figure 1, which is a reproduction of Hawley's Figure 7. This figure also represents Hawley's conception of the origin of all the major structural

[1] *Jour. Geol.*, Vol. XXXVIII, (1930), pp. 521–47. See also *Ont. Bur. of Mines Ann. Rep. 1929*, Part VI, pp. 1–58.

features of the district other than those definitely of Laurentian age. A stress couple, applied as indicated by the arrows, is assumed to have produced *en échelon* folds in the Southern Sedimentary series, analogous to folds produced experimentally in tinfoil and rubber sheets in W. J. Mead's well-known experiment.[1] With continued deformation, failure by shearing finally occurred along the east-west fault surface shown in the center of the diagram. Eastward movement of the lavas and Steep Rock Lake series to the north of the fault crushed them against the resistant granite mass to the east, thus accounting for the dominating structures in these series. All the structures, according to this interpretation, originated during a single period of deformation later than the Steep Rock Lake series in age. Let us assume for the moment that the structures were actually produced in the manner described.

FAULT MOVEMENT

The nature and magnitude of the movement along the east-west fault is of great importance in considering the possible age relations of the Southern Sedimentary series. Hawley discusses the nature of the movement at length and concludes that the main slip has carried the south side upward and westward at an angle of about 30 degrees.[2] A movement of considerable magnitude is indicated by the intense schistosity along the fault zone and the marked discordance in structural trends on opposite sides of the fault. Again, on the "closely related" northeasterly trending fault, a large movement must be inferred to explain the abrupt truncation of the Steep Rock Lake series.

JACKFISH LAKE CONGLOMERATE

A small body of conglomerate $1\frac{1}{2}$ miles north and west of Jackfish Lake has figured prominently in earlier discussions of the age of the Southern Sedimentary series. Various interpretations of its relations have been offered. Because it contains granite pebbles and others resembling the Keewatin lavas, it has been agreed that the conglomerate is post-Keewatin in age. This fact, coupled with its occurrence between the lavas and the fine sedimentary schists to the

[1] "Notes on the Mechanics of Geologic Structures," *Jour. Geol.*, 1920, p. 519.

[2] *Op. cit.*, p. 533.

south, accounts for the importance assigned to it. Hawley evidently has studied this occurrence very carefully and concludes that the body is most probably a down-faulted wedge.[1] In this he differs from earlier observers, but all would no doubt admit the possible presence of a fault on the south side of the conglomerate.

AGE OF THE SEDIMENTS

The reasoning used by Hawley in arriving at the conclusion that the structural relations favor a post-Keewatin age for the Southern Sedimentary series is given in the following quotation from his paper:

> Consider the faulted nature of the Jackfish Lake conglomerate and the southern sediments. If the two represent near-shore and off-shore phases, respectively, of one age of sediments, the faulting required to bring the two together in their present form is not excessive. To assume, however, that the finer sediments are pre-Keewatin requires either a much greater amount of displacement along the fault, or, if the conglomerate was laid down on the eroded contact of the sediments and Keewatin, the folding of the southern series must antedate the faulting by at least one and possibly two geologic periods. In the first case it has been shown that the fault is not a great overthrust from the south but more of a horizontal shear. In the second case all of the structures may be related to one major period of deformation. The probability, then, is that the Southern Sedimentary series is post-Keewatin as is the Jackfish Lake conglomerate.[2]

The weakness of the foregoing argument must be apparent. If the sediments originally lay beneath the lavas, it is obvious that no "great overthrust" would have been necessary to bring them up to their present position. A movement along a steeply dipping fault surface with a vertical component commensurate with that assumed on the fault which truncates the Steep Rock Lake series could have been adequate. In this connection it should be remembered that the original thickness of the lava series in this area is not known and that a large part of it may have been removed by erosion before the main period of deformation. It is obvious, therefore, that the movement required to bring up a prelava series, as indicated above, need not have been excessive, nor need it have been greater than that implied by Hawley's explanations.

The field evidence is stated to indicate a fault movement whereby

[1] *Op. cit.*, p. 541. [2] *Op. cit.*, p. 542.

the south side moved westward and upward. Since the south side is the upthrow side, it should have been more deeply cut into by erosion following the fault movement; and the rocks there exposed, after peneplanation, should be older than those to the north of the fault. In other words, the sediments should be older than the lavas.

Again, it is difficult to harmonize Hawley's interpretation of the fault movement with the view that the Jackfish conglomerate is a shore phase of the Southern sediments and that both are post-Keewatin. On this hypothesis, since the south side moved upward and toward the west, one must assume that before the faulting, the Jackfish conglomerate lay above, and a considerable distance to the west of, the fine sediments now in contact with it. Furthermore, it must be assumed that the fine sediments in question lay in a deep northward embayment of the basin of deposition to account for the thickness and relative fineness of the sediments. But, if such relations existed, how does it happen that the fine sediments do not occur to the north of the fault and east of Jackfish Lake at the present time? The fault must have cut off a considerable body of fine sediments, which, lying to the north of it, would have been shifted downward and eastward, relatively. These should have been less affected by erosion and hence more completely preserved than the part to the south of the fault. Actually, fine sediments are found now only to the south of the fault.

The foregoing considerations lead to the conclusion that, if Hawley's structural interpretations are correct, the Southern Sedimentary series is pre-Keewatin.

In addition to the points already treated, two others are cited by Hawley in support of a post-Keewatin age for the Southern Sedimentary series. These are:

[1] No definitely recognized Laurentian granites have been found intruding the sediments of disputed age, though granites of a later period seem abundant. Similarly post-Keewatin or Keewatin basic intrusives are found along the northern border of the sediments, but none of these has been proved intrusive into the strata.

[2] The southern sediments have been traced west to Rainy Lake, where there is still some doubt as to the structure, whether faulted or not. Grout has traced these on southwest to Minnesota where he correlates them with the Knife Lake slates of Lower-Middle Huronian age.[1]

[1] *Op. cit.*, p. 546.

The evidence of the intrusives is entirely negative and, while suggestive as stated, cannot be taken as a proof of age. With regard to the granites it should be noted further that the age classification of many of the bodies in this district is based solely on lithology or the relation borne to the Southern Sedimentary series itself. Experienced workers in the pre-Cambrian generally agree that lithology is at best a doubtful criterion. Intrusive relations to the Southern Sedimentary series mean nothing in this case, since the age of the sediments is the main point in dispute. If negative arguments are to be considered, it may be said that because the Southern Sedimentary series has not been found in erosional contact with any body of granite a pre-Laurentian age is indicated.

The correctness of Grout's correlation is still in doubt; so need not be considered further here.

ORIGIN OF THE STRUCTURES

Up to this point Hawley's explanation of the structures on the basis of one major period of deformation has been followed. Let us now consider the possibility that two major periods of deformation are represented in these structures. Earlier interpretations have assumed this, but opinions have differed as to the position of the Southern sediments with respect to each. Referring again to the paragraph quoted from Hawley's paper, we are told that the possibility that the folding of the Southern sediments antedated the faulting by one or more geologic periods should not be entertained, since the author has shown how all of the structures may be related to one main period of deformation. While it may be granted for the moment that Hawley's explanation of the structures is a plausible one, such an important alternative is worthy of more careful consideration. Lawson has shown that two periods of deformation have affected the region, each accompanied by granitic intrusions.[1] Structures associated with the earlier of these commonly have an east-west trend. If the Southern sediments are pre-Keewatin, they should have been affected by this early deformation; and it is possible that the close folding now found developed mainly at that time. The absence in the Southern sediments of structural features clearly related to the later deformation in which the Steep Rock Lake series

[1] A. C. Lawson, *Geol. Surv. of Can., Mem. 40*, p. 80.

was involved has been cited as an objection to this hypothesis. This is a debatable point. It is conceivable that a superficial series of sediments might be folded while others more deeply placed and a few miles away might show only slight effects, especially if they had been closely folded and partly recrystallized at an earlier time. It should be noted, also, that certain minor structures in the Southern sediments, as cleavage 3, described by Hawley, and some of the drag folds, may be related to the later deformation. Hawley infers folds pitching in both directions along their axes. While this condition might result from a single period of folding, it may be due in part also to transverse flexures related to the folds in the Steep Rock Lake series. One may even adopt the view, following Hawley's suggestion, that the east-west fault developed in connection with the later deformation and permitted crushing of the lavas and sediments to the north of it against the granite mass to the east, without causing important modifications in the structure of the sediments to the south of it. However, this appears to be an unnecessary assumption, and it is thought to be equally likely that the faulting occurred at some later time.

It is worthy of note, also, that the structural trend in the lavas to the north of the fault and east of Steep Rock Lake is approximately east-west, parallel to that of the Southern Sedimentary series and to the trend of the body of Laurentian granite which has intruded the lavas to the north. These relations are similar to those found in orogenic belts the world over. It seems more than likely that this structural trend was impressed as an accompaniment of the Laurentian igneous invasion and that the deformation and igneous intrusions of the Algoman period were controlled to a considerable extent by the Laurentian structures. It does not seem reasonable to assume, as Hawley does, that the later (Algoman) deformation has obliterated practically all evidence of the Laurentian diastrophism from this area except the granite bodies themselves. In other words, the hypothesis rejected by Hawley appears to fit the facts better than that which he supports.

MECHANICAL CONSIDERATIONS

From a consideration of the stress-strain relationships involved, it appears at least doubtful whether one is justified in extending the

results of Mead's experiment to explain close folding in rocks, even though the relations may appear similar. In the case being considered, it is assumed that deformation of the sediments resulted from pure horizontal shear. Under these circumstances, fold axes develop initially at about 45° to the applied stresses (parallel to *ab* in Fig. 2). As deformation continues, the fold axes are rotated so that they form smaller and smaller angles with the applied stresses. It may be shown that, when the axes make an angle of 10° with the stresses, two points on opposite sides of the deformed zone have been displaced nearly five times the width of the zone, relatively to one another (see Fig. 2). If the angle is 5°, the displacement must have been ten times the width of the zone. In the case of the Southern

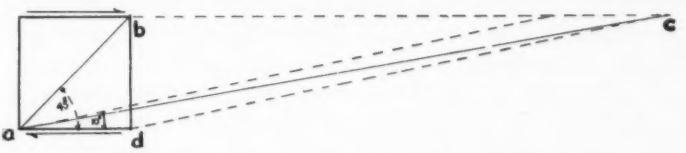

FIG. 2.—Diagram to show the extreme deformation required to cause rotation of axes of folds produced by horizontal shear, from their initial positions at 45° to the applied shear to a 10° inclination. $\frac{bc}{bd}=4\frac{3}{4}$; $\frac{ab}{ac}=4$.

sediments, the width of the zone, as preserved south of Jackfish Lake, is about 5 miles. It may have been much wider, since granite intrudes the belt on the south side. On the foregoing basis, the displacement of the south side westward must have been 20 miles or more in order to explain the folding. To the west, the band maintains the same general lithological and structural characteristics, but greater widths are observed. South of Shoal Lake the width is about 18 miles.[1] To produce the folding here on the same basis, the south side must have moved westward 80 miles or more, depending on the angular position of the fold axes with respect to the assumed stresses. Furthermore, the stretching along the fold axes (the greatest strain axis), due to displacements as above, would have amounted to from four to nine times their original lengths. Original rock textures are preserved to such an extent that much of this could not have occurred by rock flowage. If it is assumed that great elongation has

[1] A. C. Lawson, *Can. Geol. Surv. Ann. Rept. 1887*, Part F, p. 100.

occurred by slippage along innumerable vertical shear planes, the possibility of close folding is precluded, since the necessary shortening transverse to the theoretical fold axes would have been accomplished by the same movements. Failure under tension seems to be the only alternative; and, therefore, it is extraordinary that tension cracks and faults normal to the fold axes are not a conspicuous feature in the Southern Sedimentary series. In this connection it is of interest to note that Mead records the occurrence of tension cracks across the folds in his experiment. These formed as a result of a comparatively small movement. In the case of the Southern Sedimentary series, it is obviously unreasonable to assume that the enormous elongation implied by Hawley's hypothesis could have occurred mainly by the formation of tension cracks and normal faults. It appears, then, that the present condition of the series does not support Hawley's hypothesis.

At this point, it may be observed that, under any theory, the stress effective in producing the folds of the Southern Sedimentary series was a compression normal to the fold axes. Enormous horizontal movement and extreme stretching must be assumed to have occurred in addition to the shortening by compression, only if one assumes that these folds were produced solely by the horizontal shear that caused the fault. There is nothing in the structural set-up as described by Hawley, or in the known facts of geological history, which requires that the folds and the fault be so related. In fact, the only thing which suggests such a relationship in the case of the Southern sediments is the slight inclination of the fold axes to the fault surface. This relation could occur equally well (1) if the fault and the folds formed together under the action of a north-south compression combined with an east-west shear or (2) if the fault and the folds originated at different times and under different stress conditions. In either of these cases, the mechanical difficulties inherent in Hawley's hypothesis are eliminated.

Referring to the first of these alternatives, the condition of a small element within the belt of sediments is represented by Figure 3, where S is the shear and P the compression. If the shear alone were effective, the maximum compressive stress within the element would occur on the diagonal plane ab. When the compression P is added,

the maximum compression occurs on a plane inclined at a more acute angle (α) to the applied shear. The value of α depends on the relative magnitudes of P and S. It can be shown that if $\alpha = 10°$, $P = 5.5S$, and this is the condition which would fit approximately the field relations as interpreted by Hawley. In other words, if the shearing stress assumed by Hawley had been combined with a north-south compression 5.5 times as great, the folds would have formed with axes inclined at 10° to the fault. A moment's further consideration shows, however, that in avoiding one mechanical difficulty another has been introduced, for it is not possible to explain the folding of the Steep Rock Lake series by the action of the same forces. In that series, the fold axes trend in a northwesterly direction, which is nearly parallel to the direction of maximum compression, instead of at right angles to it.

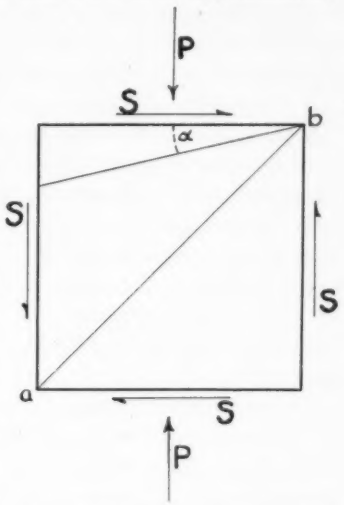

FIG. 3.—Diagrammatic representation of a unit cube under a north-south compression P and an east-west shear S.

From the foregoing it appears that all of the structures in the district cannot be accounted for satisfactorily by assuming only one main period of deformation. This conclusion is in agreement with those drawn for different reasons in earlier parts of this paper.

SUMMARY

The main points made in the preceding discussion may be summarized as follows:

1. Hawley's interpretation of the movement along the faulted contact of the Southern Sedimentary series with the Keewatin lavas favors the view that the sediments are older than the lavas, although the conclusion he draws is the opposite of this.

2. No convincing field evidence to the contrary has been recognized.

3. The hypothesis advanced by Hawley to explain the origin of the structures during one major period of deformation is mechanically improbable and not in accord with certain well-established facts of geological history in the district.

The alternative view which, in the writer's opinion, accords best with the available data is summarized below, where the main events are listed in the order of their occurrence.

1. Deposition of Southern Sedimentary series.
2. Extrusion of Keewatin lavas.
3. Laurentian deformation and batholithic intrusion (main folding of Southern Sedimentary series).
4. Erosion.
5. Deposition of Steep Rock Lake series.
6. Algoman deformation and batholithic intrusion (folding of Steep Rock Lake series).
7. Faulting—may be related to Algoman deformation or much later.
8. Prolonged erosion.

It should be noted that the foregoing outline agrees, in the main, with views expressed by T. L. Tanton,[1] though Tanton did not recognize extensive faulting along the contact of the Southern Sedimentary series with the Keewatin lavas.

While the outline above seems to the writer to accord with the facts as known at present, it is clear, from the contradictory evidence that has come from this district, that more detailed and extended field studies will be necessary before any general agreement can be reached.

A REPLY BY J. E. HAWLEY

Professor Gill's discussion of the preceding paper is welcomed. Though adding to the already long list of contradictory conclusions drawn from the Steep Rock Lake area, it renews the belief that only additional field evidence will aid in solving the problems. Allow me to indicate, first, that in no way am I opposed to the existence of pre-Keewatin sediments in some of our pre-Cambrian areas; and,

[1] T. L. Tanton, "Recognition of the Coutchiching near Steep Rock Lake," *Trans. Roy. Soc. Can.*, Vol. XX, sec. IV (1926), p. 49.

second, that for practically every argument favoring a pre-Keewatin age for the Southern Sedimentary series an equally forceful one may now be cited in support of a postlava position. Outside this particular area the work of Tanton is opposed to that of Grout, and the conclusion best drawn seems to be that the question is as far from solution as when first recognized.

Conclusions reached in the original paper, to which objections have been taken, deal both with a hypothesis suggested for the origin of the structures and also with evidence as to age of the rocks. Unfortunately, as far as advancement of our knowledge of the situation is concerned, apparent weaknesses in the theory do not support, necessarily, the Coutchiching cause, since, even using the general succession of events as outlined by Gill, the sediments may as well be considered younger than the lavas as older, corresponding perhaps with the Timiskaming sediments of other areas.

The hypothesis, of course, was intended to be applied only if the Southern sediments are definitely post-Keewatin. Obviously, the story would be different were they Coutchiching. It has been criticized somewhat illogically, as being "opposed to certain established facts of geologic history" and again, as presenting "grave mechanical difficulties." Additional objections to the hypothesis are based on assumptions as to the general geologic situation prior to the deformation, and disappear if other, equally logical, assumptions are made. The particular "established facts" appear to be that the region was affected by both the Laurentian and Algoman periods of orogeny. Because the hypothesis attributes most of the structures to the latter period, in what, after all, is a limited area, it has been construed that necessarily all previous periods of orogeny have been denied. Statements, however, appear in the original article[1] that both Laurentian and Algoman structures have easterly trends, and that here the later naturally would "mask" the earlier. That the construction, moreover, is entirely unfair is shown by the occurrence of the true "Seine" sediments a short distance to the west at East Shoal Lake, where they lie in easterly trending folds, parallel and contiguous in places with the Southern sediments. As the true "Seine" are definitely post-Keewatin and Laurentian, there is no

[1] *Jour. Geol.*, Vol. XXXVIII (1930), p. 537.

reason to question that their structures were produced in Algoman time, but in no way does their parallelism to Laurentian structures call for the elimination of that period of disturbance.

The mechanical difficulties enumerated follow logically from the interpretation that the structures are attributable to "pure" shear; and the magnitude of the horizontal displacement and stretching required, makes the hypothesis appear improbable, even though we lack data as to what these quantities may actually be. It was not intended, however, that the deformation resulted only from pure shear in an east-west direction, but rather that this was the dominant stress and that a prominent movement in this direction occurred. Under the hypothesis, all that is required is that such be the case and a considerable element of compression is possible. It should be noted, also, that in such a heterogeneous group of rocks as are found in the area, ranging from granite to (possibly already folded) lavas, and cappings of later sediments, the strain resulting most probably would not be homogeneous, nor would the relative movement be the same as the total movement. A type of distortion which better meets the case than that of pure shear and requires a reasonable amount of displacement is illustrated below (Fig. 4). Here a block is deformed by such a combination of shear and compression that the contained sides do not change essentially throughout. It is not necessary, however, that they remain absolutely the same. Assuming at least part of the mass as capable of yielding by folding, and in this case that the volume remains more or less constant, we have $ABCD$ distorted to $A'B'CD$ by a shear approximately proportional to AE, and by compression proportional to EA', $AE:A'E$ as 1:0.77, that is, the east-west shear is dominant. Unlike the case of pure shear, a decrease in horizontal area is required commensurate with an increase in the vertical dimension. The apparent east-west displacement is 0.9 times the width of the block; the elongation along the

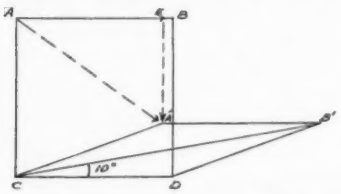

FIG. 4.—Diagram showing the deformation and displacement required if the stress is a combination of shear and compression.

diagonal, 1.4; and the vertical elevation, 2.9 times the original depth involved in the deformation. The latter would vary, depending on whether the folds are parallel or similar and whether the block was cubic or a prism. With the sediments in isoclinal folds, the depth might be measurable in thousands of feet rather than in miles, and the required elevation seems analogous to that in some folded mountains. In so far as the component of pure shear increases over north-south compression, the horizontal area will decrease less rapidly, and the total vertical elevation will be less. As the deformation progresses, the horizontal elongation, at first parallel to the axis of greatest strain, eventually becomes the direction of intermediate strain, and greatest relief or elongation is upward. The axial planes of folds then would be parallel to the intermediate axis of strain, as they are in folds produced by straight compression.

Within the sediments, as indicated by Gill, folds would be expected with their axial planes initially at 45° to the shearing stress. Rotation of the axes might occur in part by adjustments in the folds themselves, allowing for some plasticity; in part by bodily rotation; or by flowage and minor slipping along shear planes parallel to the contact fault. Tensional phenomena, normal to the elongation, in cases of intense folding under containing pressures, are seldom prominent and their absence or scarcity here seems of little significance.

To the north, in the Keewatin, is evidence of the easterly movement, reflected in the sediments by the schistosity and cleavage. The lavas, possibly lying originally in easterly trending folds of Laurentian age, have been so buckled in a north-south direction, and the Steep Rock Lake series infolded, that it is not difficult to conceive of their structures resulting from an easterly drift of this part of the block. Compression would tighten the folds and elevate the mass. The granite, presumably Laurentian, would remain relatively a competent buttress. Apparent shortening of the lavas in an east-west direction gives us some measure of the movement. That indicated by the folds mapped is approximately 7 miles. A still greater movement may yet be explained by similar folding to the west and by a bodily movement of the northern portions along east-west shear planes, such as the contact fault. The mechanical difficulties in the hypothesis, as modified, are thus considerably lessened, and

displacements required are reduced to within reasonable limits. However, it is not urged that this theory is more reasonable than the succession of events as outlined by Gill, but merely that it is a possibility.

Turning now to the evidence regarding the age of Southern sediments, we find that practically all but the Jackfish Lake conglomerate may equally well be interpreted in opposite ways. It is apparent that even this occurrence falls in the same category, and the conclusion was reached that it was of "a general wedge shape lying along the major fault plane" and "of questionable value as regards the age of the adjacent finer sediments."[1] To explain the position of the conglomerate under the two theories requires an entirely different geologic set-up in each case. That of Gill is contained in his discussion. That of the writer is as follows: Prior to folding and faulting, the Southern sediments were laid down largely to the south of the exposed Keewatin, so that their original contact with the latter is necessarily close to, if not identical with, that now visible. This was originally Lawson's idea when classifying them as "Seine." Thus, it is not necessary to explain the absence of sediments "north of the fault and east of Jackfish Lake." That such a straight, non-conglomeratic contact between sediments and lavas is possible is well illustrated by the occurrence in other areas of similar (Timiskaming) sediments which overlie the lavas, lack extensive basal conglomerates, and have been arched into easterly trending isoclinal folds parallel to the Keewatin.

The Jackfish Lake conglomerate is interbedded with finer sediments, similar to the main mass to the south, and corresponds closely in strike and dip. Its original distribution may have been very local. Faults appear to bound it on the north and south. The structural data are too obscure to establish the conclusion that it is a downfaulted wedge and therefore came from the west. It may even have come with the Southern sediments from the east, which seems necessary if it is to be correlated with the Steep Rock Lake conglomerates. Relative vertical movement at this point is not accurately known and not necessarily the same as farther east. Bearing in mind, then, the possibilities as to its original local distribution, the

[1] *Op. cit.*, p. 541.

great similarity of intercalated finer sediments to those adjacent, and its nearly concordant structure, it is reasonable to suppose that the Jackfish Lake conglomerate was once an integral part of the sediments to the south.

On the other hand, assuming the Southern series to be prelava in age, how does it happen that a mass of postlava conglomerate reached its present position? The older sediments and Keewatin supposedly were folded in Laurentian time. Erosion removed any overlying Keewatin and laid bare the essentially vertical sediment-lava contact. Following this, the conglomerate was deposited, presumably as flat beds. The next event recorded is that of faulting along the sediment-lava contact. The fault plane is approximately vertical. Movement along it appears greatest in a horizontal direction. Judging from its schistose nature, the fault zone was an area of some compression. Yet, on this theory we are asked to believe the conglomeratic beds were caught in the fault and necessarily squeezed down into the contact between older sediments and lavas and rotated to a vertical position. They are not now in contact with the lavas on which they were deposited. Their attitude might be explained were the fault largely an overthrust from the south. For that reason, this possibility, which is untenable, was mentioned.[1] Or again, one might suggest the aid of early block faulting followed by later shearing. Thus a narrow block of conglomerate would be dropped between sediments and lavas, and later shearing would accomplish the tilting. While this has possibilities, it obviously requires corroboration by field evidence; but not even then can it be admitted as rigorous proof that the Southern series is Coutchiching. It would indicate merely that the conglomerate is younger than the sediments, but would not tell the age of the latter with respect to the Keewatin.

To sum up, none of the data from the Steep Rock Lake area afford safe ground for conclusions as to the age of the Southern Sedimentary series. This is attributable largely to the faulted nature of their contact with the Keewatin, and proof positive must be sought in adjacent areas where this condition is lacking.

[1] *Jour. Geol.*, Vol. XXXVII (1929), pp. 542, 546.

ALGAE AND ALGAL BEDS IN THE BELT SERIES OF GLACIER NATIONAL PARK[1]

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ABSTRACT

Rocks of the Belt series in Glacier National Park present evidence of repeated sedimentary cycles closely associated with changes in level, sedimentation apparently being marine. Conforming to stages in these cycles several new formations are described and others are redefined. At several horizons beds of fossil algae occur, containing both new and previously described species of *Collenia*, and species of *Newlandia*, *Weedia*, and *Beltina*. Algal life-forms are closely correlated with sedimentary types, remaining uniform over wide areas.

INTRODUCTION

The presence of fossil algae in the Belt terranes of Glacier National Park has been known since 1906, when Walcott named and figured[2] *Cryptozoan* (now *Collenia?*) *frequens* from the Siyeh formation on Little Kootenai Creek. Daly, six years later,[3] figured as a concretion an apparent algal colony from the Gateway formation of the Galton Range, which is approximately equivalent to the lower Sheppard of Glacier National Park; while in 1914 Walcott[4] described and illustrated several algae from the same region without recording, however, the presence of fossil algae in other formations than the Siyeh.[5]

It was with some surprise, therefore, that we found in the course of field work carried on during the summers of 1927 and 1928, that fossil algae are abundant at several horizons in three of the major geologic formations of Glacier National Park. The purposes of this paper are to describe certain of these algae, to discuss their stratigraphic relationships, and to review evidence concerning the environments in which they lived.

Types, except plesiotypes of *Collenia undosa* Walcott, are in the

[1] Contributions from the University of Cincinnati Museum. Geology and Paleontology. No. 13. Read before the Paleontological Society, December 27, 1929.

[2] *Bull. Geol. Soc. Amer.*, Vol. XVII (1906), Pl. 11.

[3] *Geol. Surv. Can., Mem.*, 38 (1912), Part 1, Pl. 14.

[4] *Smithsonian Misc. Coll.*, Vol. LXIV (1914), pp. 108, 113.

[5] Willis refers to "many flattened concretions" in the Altyn, which doubtless are the forms described as *Collenia columnaris* of this paper. See *Bull. Geol. Soc. Amer.*, Vol. XIII (1902), p. 317.

University of Cincinnati Museum, whose catalogue numbers, prefaced by U.C.M., are given in the plate explanations.

STRATIGRAPHY

The first general section of the Belt formations in the Waterton Lakes–Glacier National Park region was that furnished by Dr. George M. Dawson, in 1875.[1] Dawson, however, regarded the Belt strata as Cambrian and younger in age, and assigned no formation

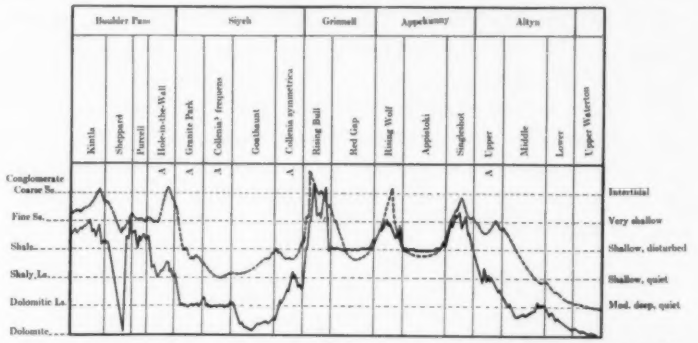


FIG. 1.—Fluctuations in the level and sediments in the belt series of Glacier National Park. Continuous line represents lithologic types, prior to metamorphosis; broken line indicates dominant conditions of deposition. *A* marks alga-bearing members.

names. Twenty-seven years later, Willis, in his paper on "Stratigraphy and Structure, Lewis and Livingston Ranges, Montana,"[2] advanced the opinion that the strata in question were Algonkian (Proterozoic) and proposed six formations:[3]

	Feet
6. Kintla Argillite—Argillites, calcareous argillites, quartzites	800
5. Sheppard Quartzite—Yellow quartzite overlying lava flow	700
4. Siyeh Limestone—Limestone with some argillite	4,000
3. Grinnell Argillite—Argillite, dark red	1,000–1,800
2. Appekunny Argillite—Argillite, gray, black, greenish	2,000
1. Altyn Limestone—Limestone, argillaceous near top	1,400
(Thicknesses approximate)	

[1] *British Boundary Commission Report on the Geology and Resources of the Region in the Vicinity of the Forty-ninth Parallel, 1875*, pp. 67–68.

[2] *Bull. Geol. Soc. Amer.*, Vol. XIII (1902), pp. 305–52. The Livingston range of this paper is the Clarke of more recent contributions, especially that of Daly.

[3] *Ibid.*, pp. 316–17.

To this sedimentary series Daly[1] added a seventh formation: the Waterton Dolomite, which lies beneath the Altyn at Cameron Falls and other localities near the shores of Waterton Lake, north of Glacier National Park. He also named the Purcell Lava, a series of subaqueous diabase flows which in Willis' scheme separates the Siyeh and the Sheppard formations.

Neither Willis' paper nor Daly's, however, stresses the character which we find most significant in the entire Belt series of the Lewis and Clarke ranges. We refer to the pronounced evidence of sedimentary cycles, and of correlated cycles involving elevation, oscillation, and depression of the basin of sedimentation. Accepting these latter cycles as furnishing a diastrophic basis for classification, we advance the following provisional, generalized section, drawn chiefly from field work in the Lewis range, south of Ahern Pass, and in the Clarke (or Livingston) range near Boulder Pass and in Waterton Lakes National Park.

SECTION OF THE BELT SERIES IN GLACIER AND WATERTON LAKES NATIONAL PARKS

	Feet
6. Boulder Pass formation	
d) Kintla member	
(4) Argillite, thin-bedded, more or less sandy, interbedded with quartzite. Colors of the argillites range from brown to red, with some purplish and green layers; the quartzites are white, greenish, or red. Ripple marks and mud cracks common; casts of salt crystals present in sandy layers	460+
(3) Argillites, thin-bedded, and chiefly red, interbedded with red, gray, and brown sandstones and quartzites, and limestones, gray, magnesian, irregularly oölitic. Some concretions which may represent algae	300
(2) Amygdaloid sill, green to purplish	40–60
(1) Argillite, thin-bedded, red to brownish, interbedded with thin layers of red quartzite	60–70
c) Sheppard member	
(2) Dolomite, thin-bedded, gray weathering to ocher, with some thin lenses of magnesian quartzite. Heavy major beds and joints give a superficial appearance of	

[1] *Geol. Surv. Can. Mem. 38* (1914), Part 1, p. 50. Daly considers the rocks here designated "Belt" to be of Cambrian age.

	Feet
heavy bedding on Boulder Pass. Near Swift Current Pass the beds become compact, and "molar tooth structure" (Daly) is common	500–600
(1) Argillite and metargillite, thin-bedded, silicious, green, brown, or reddish, with interbeddings of quartzite and, near the top, of dolomite like that of No. (2). Basal beds identical with those below the Purcell Lava; ripple marks common	20–50
b) Purcell Lava	
(1) Extrusive lava, basic, dark green, in three to seven distinct flows with interbeddings of green metargillite. Ellipsoidal masses or "pillows," flow structures, pipes and inclusions of rolled, highly metamorphosed sediments common. Thickness variable, the maximum noted being in the Boulder Pass region	100–200
a) Hole-in-the-Wall member[1]	
(3) Metargillite, medium-bedded, finely banded, green. Large ripple marks in the upper portion; *Collenia* in the lower	16
(2) Metargillite, quartzite, and minor beds of conglomerate, the main mass consisting of red to buff, sandy metargillites which are abundantly mud-cracked, ripple-marked, and in spots cross-bedded. Well exposed on the slope above Granite Park chalet	300–350
(1) Argillite, green to buff, finely banded, grading downward into gray-buff argillaceous limestone, mud-cracked and ripple-marked. On Swift Current Mountain the base of the green member is the horizon of *Collenia undosa;* the mud-cracked portions beneath thin and grade into the upper Siyeh. Maximum thickness	75
5. Siyeh formation	
d) Granite Park member	
Limestones, thin-bedded, gray, with interbeddings of argillite and conglomerate, the latter consisting of limestone pebbles. Some oölites in lower portion; upper beds commonly crowded with large colonies of *Collenia* sp. Well exposed along the Garden Wall near Granite Park, but more fully developed in Hole-in-the-Wall cirque	185

[1] At the head of Starvation Creek, in the Clarke Range of Alberta, Daly records 1,100 feet of gray, greenish, and reddish metargillites which appear to represent the Hole-in-the-Wall member of the Boulder Pass and the Granite Park beds of the Siyeh. See Daly, *Geol. Surv. Can., Mem., 38* (1912), p. 72.

Feet

c) *Collenia? frequens* zone

Limestones, massive, gray, crystalline, in places silicious. Basal member 30–50 feet thick; upper portions variably interbedded with thinner non-algal limestones..... 80–100

b) Goathaunt member

Limestone, massive, impure, magnesian, dark gray weathering to buff; some interbeds of dolomitic metargillite and a few thin beds of sandstone. Molar tooth and shear structures common in upper portions. Can be studied throughout Glacier National Park; most accessible on the trail to Swift Current Pass ..... 2,000+

a) *Collenia symmetrica* zone

Metargillite, quartzite, and sandy to argillaceous limestones, containing at several horizons beds of *Collenia symmetrica* n.sp. Northward from Cut Bank Pass, where they are best exposed, these beds thicken and become more clastic..... 500–900

4. Grinnell formation

b) Rising Bull member

Metargillite, dark red to greenish, in beds 1–3 feet thick, showing slaty cleavage; interbedded with red, gray, white, and greenish quartzite and conglomerate. Argillite balls abundant in some layers of quartzite; mud cracks and coarse current ripple marks common; some layers bear rain-prints. Quartzite increasingly prevalent toward the top; base intergrades with the Red Gap member. Well exposed along the trail over Gunsight Pass, in the Two Medicine region, and on mountains bordering Swift Current Valley..... 425–750

a) Red Gap member

Metargillite, in thin minor but thick major beds; interbedded near bottom and top with minor layers of quartzitic sandstone and red, sandy argillite. Forms the mass of Mount Rockwell, in the Two Medicine Valley..... 1,050–1,800

(On King Edward Mountain, British Columbia, 3 miles north of the international boundary, Daly found a 20-foot lava, "basic, amygdaloidal, extrusive," 175 feet above the base of the Rising Bull member. In Waterton Lakes National Park, near the union of Bauerman and Lone brooks, are exposures of a crystalline, basic intrusive near the top of the Red Gap member. The same sill may be seen on either side of Blackiston Valley.)

Feet

3. Appekunny formation

c) Rising Wolf member

Quartzite, thick-bedded, greenish to red, with subordinate beds of gray and reddish metargillite. Mud cracks and ripple marks common; the metargillites contain much sand, distributed in thin sheets and lenses. Exposed on the south flank of Rising Wolf Mountain, and on many other peaks 200–500

b) Appistoki member

Metargillite, thin to thick-bedded with minor beds of silicious argillite and quartzite. On Rising Wolf and Appistoki Mountains, in the southern part of the Lewis Range, this member consists of a lower series of brownish to black metargillites and an upper greenish series which form heavy ledges and falls. Northward to Blackiston Brook, Alberta, the member becomes more highly silicious, with beds of quartzite; the color becomes green in the lower portions. Daly records a 75-foot dolomite member in the Clarke range. Mud cracks and ripple marks common, but not so well developed as in the Grinnell 2,000–2,200

a) Singleshot member

Metargillites with interbedded, thick quartzites and dolomitic sandstones. Colors range from brown through greenish and white to red. Mud cracks and coarse ripple marks common. Not well developed in the Two Medicine Valley; best seen on Singleshot Mountain, near St. Mary Lake 300–400

2. Altyn formation

Dolomites, limestones, and arenaceous magnesian limestones with interbeds of sandstone whose facies differ so greatly as to make names useless. In the Two Medicine Valley only the upper part of the formation is present: it consists of arenaceous, magnesian limestones bearing *Collenia columnaris* in considerable numbers. In the Swift Current Valley the same member is present, with algae in great abundance and a great deal of coarse, rather angular sand. Ripple marks are prevalent in certain layers and mud cracks are distinguishable in some, along with edgewise conglomerates. Along Cameron Brook, and on Cameronian and Crandell Mountains, Waterton Lakes National Park, the entire thickness of the Altyn is highly arenaceous; on Mount Crandell and Vimy Peak the sequence is considerably complicated by low-angle thrusts. Thickness given by Daly as 3,500

	Feet
1. Waterton formation	
Dolomite, massive, resistant, dark gray, weathering to brownish red and buff	Unknown

In all probability, the confession of ignorance as to the thickness of the Waterton should be extended to the Altyn as well. In the southern part of Glacier National Park, only the upper portion of the formation is present, lying directly upon the crumpled Cretaceous shales and sandstones. On the southern side of the Swift Current Valley, as well as in Divide, Chief, and Yellow Mountains, the formation is complicated and repeated by low-angle cross-faults. In the Waterton Lakes region, these faults increase in number and throw, so that Daly's 3,500 feet of Altyn probably contain four to seven repetitions of the upper members of the formation alone, this repetition being most clearly seen on Cameronian Mountain.

ALGAL BEDS AND HORIZONS

Beds of what seem to be fossil algae occur at several horizons in this series. The lowest lies in the upper Altyn limestones: a series of massive limestones, in some places metamorphosed into fine-grained marble, and crowded by the elongate colonies of *Collenia columnaris* n.sp. They were first seen on the south slope of Spot Mountain, at the entrance to the Two Medicine Valley, where the rock is considerably metamorphosed and the algal colonies are small. Similar beds are exposed at the upper end of McDermott Falls, and may be traced eastward along the foot of Appekunny Mountain.

It is in the talus and rock wall near Appekunny Falls, however, that the zone of *Collenia columnaris* is best seen. There it is represented by massive, light gray limestone in a single bed some 20 feet thick, and virtually the entire mass of stone is formed by colonies of this one alga. Abundant weathered sections are afforded by the large blocks which break off from the mountain face because of the creep of the underlying Cretaceous shales. Examples are shown in Plate II.

No algae have been found in the Appekunny and Grinnell formations, but near the base of the Siyeh appears the form here described as *Collenia symmetrica*, characterizing a zone 500–900 feet thick. The enclosing sediments are gray limestones containing considerable

quantities of fine clay; the algal masses are dark gray or black. In most places they lie more or less isolated in the matrix, so that distinct, flattened or spheroidal colonies may be taken out, but in one bed near the crest of Cut Bank Pass the colonies are so closely crowded as to virtually constitute the layer (Plate III). *Collenia symmetrica* appears to characterize this basal member wherever it is found, for specimens, badly weathered yet identifiable, have been found in talus or drift in the Clarke Range east of Brown Pass.

The most conspicuous algal beds, however, are those characterized by *Collenia? frequens* Walcott. They form a group of massive, resistant gray limestones which lie some 185 feet below the reddish mud-cracked argillaceous limestones and argillites which mark the base of the Sheppard. They comprise a distinct unit, the *Collenia? frequens* zone, which is readily accessible for study along the trail to Swift Current Pass (Plate IX). It may be seen whenever the Siyeh is appropriately exposed, standing out boldly on the cliff faces and furnishing an excellent datum by which variations in level of the diorite sill contained in the Siyeh may be determined.

In the Clarke (Livingston of Willis) range the *Collenia? frequens* zone was studied just above Hole-in-the-Wall Falls, where it consists of four members:

	Feet
4. Limestone, gray, massive; crowded by *Collenia? frequens* Walcott	15
3. Limestone, gray, shaly, in beds 3–6 inches thick, with numerous partings. No algae seen	6
2. Limestone, gray, massive in a single bed; composed of elongate algal colonies 3–6 inches in diameter and 20–30 inches in height, which closely resemble *Collenia columnaris* of the present paper	4
1. Limestone, gray, massive, irregularly crystalline; no bedding planes discernible. Entire thickness crowded by *Collenia? frequens* Walcott	50
Total	75

Northward, in Waterton Lakes National Park, Alberta, the *Collenia? frequens* zone appears on mountain faces where the Siyeh is exposed, while the steep southward dip in Cameronian Mountain carries it into the bed of Cameron Creek. There the main mass, No. 1 of the foregoing section, is well exposed, but the other members cannot be distinguished. North of the Blackiston Valley no

studies have been made, and the extent of the zone therefore is undetermined.

The uppermost Siyeh (Granite Park member) as developed in the lower walls of the Hole-in-the-Wall Cirque, consists of limestones of gray or buff color, with much clastic material and some minor beds of shale. "Molar tooth structure" is found in some members, and many of them contain expanded, concavo-convex algal masses apparently belonging to the genus *Collenia*. None could be found which were small enough to be collected, while the largest one, illustrated in Plate X, has a diameter of about 10 feet. No edgewise conglomerates were seen, nor were oölites.

In the Lewis range, along the trail leading from Granite Park chalet to the ridge west of Grinnell Glacier, algal beds like those at Hole-in-the-Wall may be seen, though none of the colonies reach great size. East of the Continental Divide the algae are less abundant; while near the top of the Siyeh, edgewise conglomerates and minor beds of oölite appear along the Swift Current Trail. In no case have oölites and algae been found in close association.

The red argillites of the Sheppard member of the Boulder Pass contain no algae; nor do the yellow-weathering limestones. Near the base of the Hole-in-the-Wall member, however, is a bed of compact green argillite, overlying a mud-cracked green bed, and containing abundant pinkish masses of *Collenia undosa* Walcott, apparently identical with the form found in the Big Belt Mountains. Colonies range in diameter from 1 cm. to 30 cm., the small ones being spheroidal. Although resistent to weathering, the algae do not dominate the bed in which they occur, and unlike some others, give their horizon no physiographic distinction, even though it may be traced for a considerable distance along the Continental Divide.

No algal beds have been found above the Purcell Lava, the shallow-water clastics and dolomitic or shaly limestones of the upper Sheppard and Kintla members apparently representing environments hostile to algae. A possible exception to this statement is found in No. (3) of the Kintla member, which contains silicious concretions that suggest algal masses.

ENVIRONMENT OF THE BELTIAN ALGAE

Walcott, largely because of the absence of unquestionably marine organisms from the Beltian rocks, advanced the hypothesis that they were deposited in elongate, steadily sinking, lake basins. Indeed, he went so far as to assert the probability that all known Algonkian rocks are of non-marine origin.[1]

This conclusion seems to be borne out by the recent work of Bradley[2] on the algal "reefs" of the Green River formation. There seems no doubt that the Green River sediments are lacustrine, and a comparison of Bradley's figures with those of Walcott, and with our own, shows that there is great similarity between Green River and Beltian algae. On a biologic basis alone, therefore, it appears that the Belt series is, as Walcott believed, lacustrine.

Examination of the strata themselves, however, leads to another conclusion. Attention already has been called to the prevalence of mud cracks and current ripple marks in the rocks of the Glacier-Waterton Lakes region. Without known exception the polygons between those mud cracks either are flat or strongly downwarped, the downwarping being especially marked in the bed upon which *Collenia undosa* is common (Plate VII, Figs. 3–5).

Downwarped polygons, in Kindle's experiments,[3] are formed by the drying of saline muds, although he finds that in nature some saline muds produce concave polygons.[4] Even though there are such exceptions, and others are conceivable in which non-marine sediments may show downwarped polygons, still the weight of evidence is in favor of marine, or at least saline muds as the material of the Belt strata. That some of the muds actually were saline is shown by the casts of salt crystals which are found in the Kintla,[5] Sheppard, and Rising Bull members, even though they are not so prevalent as to indicate a salt lake or very highly saline basin.

[1] *Smithsonian, Misc. Coll.*, Vol. LXIV (1914), p. 97.

[2] *U.S. Geol. Surv. Prof. Paper 140* (1925), pp. 119–20, Pl. 62*B*; *ibid.*, *Paper 154* (1929), pp. 203–32.

[3] *Jour. Geol.*, Vol. XXV (1917), pp. 135–44; *Bull. Geol., Soc. Amer.*, Vol. XXVIII (1917), pp. 905–16.

[4] *Jour. Geol.*, Vol. XXXI (1923), pp. 138–45.

[5] B. Willis, *Bull. Geol. Soc. Amer.*, Vol. XIII (1902), p. 316; R. Daly, *Geol. Surv. Can., Mem. 38* (1912), Pl. 11.

The prevalence of current ripples, in the opinion of Kindle,[1] is another evidence of marine sedimentation. Such ripples are by far the commonest ones seen in the rocks of Glacier National Park, although typical wave ripples are found at various horizons. In the Rising Bull member of the Grinnell, moreover, we have found a few "mound and pit structures," whose development in marine sediments is described by Kindle.[2] Although not diagnostic, they add their weight to evidence which already indicates marine origin.

Much of this evidence, of course, is drawn from clastic beds which contain no fossil algae. The sedimentary series, however, is remarkably unified, as already has been said, and if certain parts of the series—especially those which indicate shallow water, fluctuation and desiccation—appear to be marine, it is not probable that the limestone parts of the cycles are to be interpreted as lacustrine. We hope to return to the question at another time, after a general study of sedimentation in the Glacier Park–Waterton Lakes district; yet even now we feel justified in saying that the Belt sediments of that region, and probably of areas to the southward, are marine.

Finally, we may point out that a connection exists between environment, as represented by sediments, and the types (life-forms, in ecology) of algae present. In pure limestones, such as the *Collenia columnaris* beds of the Altyn and the *C. ? frequens* zone of the Siyeh, the algal colonies are tall, relatively slender and so closely packed that they literally must have formed the sea bottom over hundreds of square miles. In the argillites, and in those limestones which contain considerable clastic material, on the other hand, the algal masses uniformly are more or less isolated and depressed spheroidal or concavo-convex, even though the organisms seem to be specifically distinct in different formations.

ALGAE AND OÖLITES

There always must be some doubt that masses such as those considered in this paper really represent organisms, since their preservation is such that no microscopic data are available.

Our conclusion that they do is based on their similarity to the masses formed by modern algae, and to such unquestionably algal

[1] *Bull. Geol. Soc. Amer.*, Vol. XXVIII (1923), pp. 913–16. [2] *Ibid.*, pp. 909–10.

colonies as those described by Bradley. It may be well, however, for us to answer one possible objection: that the masses in question are merely pseudo-fossils, the result of inorganic processes comparable to those involved in the making of spherulites or oölites.

During our field work we have had this possibility in mind, and have sought for probable inorganic deposits of these two types. In one case we were rewarded: on Dawson Pass, in talus containing *Collenia symmetrica*, we found fragments of oölite in which the oölitic grains were black. Further search failed to reveal the bed, which must be thin, but it cannot be far above the algal layer.

In other localities, however, no oölites were found associated with *Collenia symmetrica*, whose essential characters are remarkably stable even though its shape varies. Oölites are lacking in the Altyn and the *Collenia? frequens* zone of the Siyeh, and naturally are not found in the bed of argillite which is the chief horizon of *C. undosa* Walcott. The few oölites found, along with edgewise conglomerates, in the uppermost Siyeh (Granite Park) are not associated with algae, though algae occur in related horizons less than a mile away. The horizons of abundant algae at Hole-in-the-Wall are not, so far as we could find, oölitic.

Our conclusion, therefore, is that while the conditions favoring growth of algae do not preclude the formation of oölites, there is no essential genetic connection between the two, and the formation of the masses which we regard as algal deposits cannot at present be explained as an inorganic process. On the other hand, analogy furnishes strong evidence that these masses were organic in origin.

This, of course, does not answer Holtedahl's criticisms that such forms as those described by Walcott and ourselves either are the results merely of "chemical precipitation . . . . that probably came into existence through the organic processes of living organisms,"[1] or were "formed secondarily by very important radical internal changes in the rocks. It also has been pointed out," says Holtedahl, emphasizing the opinions of English geologists, ... "that some of the characters of these structures suggest those developed by crystallization processes."[2]

[1] *Amer. Jour. Sci.*, Ser. 4, Vol. XLVII (1919), p. 96.

[2] *Ibid.*, Ser. 5, Vol. I (1921), p. 206.

For the second of these interpretations no field evidence could be found. The characters of these supposed algal colonies are surprisingly uniform at given horizons regardless of obvious secondary changes—very rarely uniform over wide areas—in the strata bearing them. Even in the matter of crystallization there is no correspondence: forms such as *Collenia undosa* and *C.? frequens* are represented by highly crystalline specimens and others in which crystallization is slight, yet their characters are unchanged. *C. columnaris* even may be traced by dark coloring in portions of the Altyn which are true marble, and these colors show the same characters seen in Plates I and II. If these characters themselves are the results of secondary changes, especially crystallization, it is strange that they are so nearly independent of them in their distribution.

Of greater weight, at least in the present case, is Holtedahl's first suggestion that the "algae" are consequences of organically initiated precipitation, but are not actual petrifactions. In favor of it may be mentioned such forms as *Weedia tuberosa* and *Collenia compacta*—the former so indefinite that we could not recognize it in the field, the latter recognizable only in selected specimens. On the other hand, we have such species as *Collenia columnaris*, *C. symmetrica*, and *C. undosa*, all forming sharply delimited masses, all as stable in their characters as any coral, all readily recognizable in the field. We wish to emphasize that, so far as general characters alone are considered, all of the forms just named are more readily and more uniformly recognizable than are members of such genera as *Prismatophyllum*, *Favosites*, or *Columnaria*. That such structures should result from chemical precipitation alone, even though originated by the action of organisms, is very difficult to believe.

DESCRIPTIONS OF FOSSILS

Genus *Collenia* Walcott

Collenia columnaris n.sp

Plates I and II

Description.—Large, irregularly columnar masses which generally stand with their long axes at angles of 80°–85° to the bedding planes. The laminae are variable in thickness; they form elongate-oval, convex layers which in cross-section describe arcs of 30°–120° and are not concentric. The extent to which

lamellae are elongated varies; in the holotype length and width are about equal, and there is no constriction of margins. Smaller specimens indicate a length about twice the width.

Remarks.—*Collenia columnaris* grows in compact beds, one colony abutting closely against the next. Widths range up to 18 cm. and heights to 40 or 45 cm. An allied form in the Siyeh, not described, is much smaller, its average width being about 8 cm., though its height is approximately that of *C. columnaris*.

A related form *Collenia kona* Twenhofel,[1] of the Lower Huronian in the Marquette region of northern Michigan, is considerably larger than *C. columnaris*, individual colonies reaching a diameter of 2 feet. The laminae of the Michigan species also are much more regularly convex than are those of *C. columnaris*, and are less depressed marginally, though the boundaries of individual colonies[2] are sharper and less flexuous.

Occurrence.—Upper Altyn, on Altyn, Appekunny, Spot, and other mountains along the front of the Lewis Range in Glacier National Park; most abundant near Appekunny Falls. Not seen in the upper Altyn of the Waterton Lakes region.

Collenia symmetrica n.sp.

Plates III, IV, and V

Description.—Masses typically are either depressed-spheroidal in form, or massively concave-convex. In some strata, however, they are depressed, concave-convex, and very irregularly sub-circular in outline. The laminae are closely spaced; they are regularly concentric, flattened or moderately convex centrally and abruptly convex marginally, where the major laminae (the only ones which show in the photographs) commonly are much compressed. In specimens which, like that of Plate IV, form distinct, depressed-spheroidal masses, the edges of the laminae are reflected and then abruptly depressed, producing the character shown in Plate V, Figure 1. Even in the crowded masses seen in Plate III, this character may be distinguished.

Another character which marks these organisms at every locality where they have been found is their black or dark-gray color, which commonly is accompanied by a carbonaceous luster. In spite of this, the limestone composing the masses is very hard, and fractures into angular blocks.

Remarks.—Of the several form-species of supposed algae represented in this paper, this gives the most convincing evidence of organic nature. The distinctness of the laminae, the persistence of such characters as the marginal crowding

[1] *Amer. Jour. Sci.*, Ser. 4, Vol. XLVIII (1919), p. 346.

[2] Twenhofel (*op. cit.*, p. 342) has proposed the term "coenoplase" for such a structure as is illustrated in Plate I, which we call a "colony." The term is useful, though its author seems to abandon it on the page following his definition, when he writes of "a group of colonies." On page 346, however, he refers to the structures as "small secondary domes" each of which "seems to have represented a more or less separate colony"; and further, as "growths of large size; dome-shaped on the upper surface." In such a multiplicity of possibilities we retain the simpler, but perhaps satisfactory term "colony."

of laminae, and their peripheral reflection, in colonies of widely differing shapes —all indicate definite growth, not governed by factors determining the gross characters of the masses.

Occurrence.—Lower Siyeh, on Cut Bank and Dawson passes, near the foot of Swift Current Mountain, and below Iceberg Lake, all in the Lewis Range in Glacier National Park.

Collenia undosa Walcott

Plate VI; Plate VII, Figs. 3–5

Collenia undosa Walcott, *Smithsonian Misc. Coll.*, Vol. LXIV (1914), p. 113; Pl. 13, Figs. 1–2; Pl. 14, Figs. 1–2.

Description.—Small specimens of this species are irregularly subspheroidal, or depressed. With increasing size the masses expand, become markedly concavo-convex and develop irregular, even botryoidal elevations upon the upper surface. Each mass consists of more or less regularly alternating fine and coarse lamellae which are subparallel to the upper and lower surfaces.

Remarks—Natural sections, which are abundant, are closely similar to the sections illustrated in Walcott's Plate 13. In general, the Sheppard specimens are more tumid than those from the Spokane formation, and are markedly concave beneath only when resting directly upon a mud-cracked surface—a condition, however, which seems to be the rule. It holds also among Walcott's specimens. Of the many shown us by Dr. Resser, several preserve portions of polygons and crack-fillings upon their lower surface, while the majority are sufficiently concave to allow for such an attachment surface.

This fact, along with the worn, broken and apparently rolled condition of some of the specimens from the Sheppard, but especially from the Spokane formation, seems to indicate that *Collenia undosa* was a littoral form, probably ranging even into the intertidal zone, where waves and currents frequently disturbed its position. One specially convincing example of such disturbance is seen in the holotype (Walcott's Pl. 13, Fig. 2) which appears to have been turned over, after attaining nearly normal size, and to have begun growth anew upon the exposed surface.

Occurrence.—Lower beds of the Sheppard formation, especially along the Continental Divide near Grinnell Glacier, the Garden Wall and Granite Park Chalet, Glacier National Park. Commonest in a green argillite overlying a mud-crack layer, which seems to be present also in the Boulder Pass district of the Clarke range.

Collenia compacta Walcott

Plate VIII, Fig. 2

Collenia compacta Walcott, *Smithsonian Misc. Coll.*, Vol. LXIV (1914), p. 112, Pl. 15, Fig. 7.

Description.—Colonies flattened and turbinate to massively laminate in growth, the most typical state being the one indicated by Plate VIII, Figure 2, in which two colonies overlap and are confluent basally. No horizontally laminate masses have been seen.

Remarks.—The close association of *Collenia compacta* with *C.? frequens* throws some doubt upon the distinctness of the two. It seems quite possible that the former, which is the less common, is but a different growth-state of the latter, though the point cannot as yet be determined.

Collenia? frequens Walcott

Plate VIII, Fig. 1

Cryptozoan frequens Walcott, *Bull. Geol. Soc. Amer.*, Vol. XVII (1906), Pl. 11.
Collenia? frequens Walcott, *Smithsonian Misc. Coll.*, Vol. LXIV (1914), p. 113, Pl. 10, Fig. 3.

Description.—Large elongate-conical or almost columnar masses which generally stand with the long axis at an angle of 65° or 70° to the bedding plane. Each mass consists of concentric, elongate-conical laminae which number eight to fifteen in the space of 1 cm.; diameter ranges from 3 to 45 cm. and height, measured along the surface, from 20 to 60 cm., or even larger. Oblique sections of specimens in which the laminae are coarse have a marked cone-in-cone appearance, which commonly is heightened by a grouping of the laminae into compound layers separated by fine laminae of dolomite.

Remarks.—There can be little doubt that this is the form described by Walcott from Little Kootenai Creek. It is best seen near Swift Current Pass, where it forms heavy beds of dolomitic gray limestone containing occasional lenses of banded, thinly bedded gray limestone. Next to *Collenia undosa* it is the most convincingly plantlike of the forms described in this paper.

Genus *Newlandia* Walcott

Newlandia sarcinula n.sp.

Plate VII, Figs. 1, 2

Description.—Small, subspheroidal masses made up of regular, concentric laminae which number nine to eleven in the space of 5 mm. On weathered surfaces the laminae are sharply separated, and there are traces of radial interlaminar pillars which suggest structures in some of the false stromatoporoids.

Remarks.—In its gross structure, *Newlandia sarcinula* closely resembles *N. lamellosa* Walcott, but its manner of growth is quite distinct. From *N. concentrica* Walcott it differs in having much finer lamellae, without alternation.

Occurrence.—Upper Altyn on Spot Mountain in the southeastern part (Two Medicine Valley) of Glacier National Park.

Genus *Weedia* Walcott

Weedia tuberosa Walcott

Weedia tuberosa Walcott, *Smithsonian Misc. Coll.*, Vol. LXIV (1914), p. 108, Pl. 11, Figs. 1, 2.

Remarks.—This is the genotype of *Weedia* Walcott, whose definition runs:

"Irregular, encrusting, and solid deposits that gathered as tubercles, ridges, and many irregular forms on the bed of the body of water in which the algae forming them lived. The specimens suggest a secondary silicious deposit in the limestones, but the concentric

laminated structure of the tubercles points more strongly to an origin similar to that of the encrustations made through the agency of Blue-green algae (Cyanophyceae)."[1]

The generic range erroneously appears as the "upper part of the Altyn limestone series interbedded with siliceous and cherty layers." This, however, cannot be the case, since no Altyn is to be found in the vicinity of Gunsight Pass, the type locality of *Weedia tuberosa*, whose horizon appropriately is given as Siyeh. In the broad region covered by Walcott's locality 400 there are several hundred feet of the lower and middle Siyeh, as well as talus from a much greater thickness, and the nature of the types fails to indicate their stratigraphic origin.

The "species" is so loosely defined, and so uncertainly a petrifaction, that we did not include it among our collections. Probably, as has been suggested, it represents a laminated algal precipitate rather than an actual algal colony; and its distinctness from the structures described as algae in this paper may be some measure of the limitations of Holtedahl's general criticism.

Genus *Beltina* Walcott

Beltina danai? Walcott

Remarks.—The upper portions of the Altyn limestone, below the *Collenia columnaris* zone east of Many Glacier Hotel, contain abundant carbonaceous fragments first collected by Weller,[2] and provisionally identified by Walcott as belonging to his supposedly merostomate genus *Beltina*. Similar fragments are common in the Altyn near "Oil City," in the Cameron Valley of Waterton Lakes National Park. As a rule, the fragments are larger than those illustrated by Walcott,[3] and suggest the thin, broken thalli of algae rather than "fragments of the carapace of crustaceans." It is as algae that White[4] has considered these remains in his recent report upon field studies of Proterozoic plants; and since his specimens are superior to our own, there seems no need for us to describe the organisms, whose specific identity certainly cannot be determined from material at hand.

[1] *Smithsonian Misc. Coll.*, Vol. LXIV (1914), p. 107.

[2] See Willis, *Bull. Geol. Soc. Amer.*, Vol. XIII (1902), p. 317. The locality at which *Beltina* is most common is shown in Pl. 47, Fig. 2, of the same paper.

[3] *Bull. Geol. Soc. Amer.*, Vol. X (1899), Pls. 25, 26; *Smithsonian Misc. Coll.*, Vol. LXIV (1914), Pl. 22.

[4] *Carnegie Inst. Wash., Year Book*, No. XXVIII (1929), p. 393.

PLATE I

Collenia columnaris n. sp. The holotype, an isolated colony from such a mass as is shown on Plate II, Fig. 2. (U.C.M. 4747), ×0.5.

PLATE II

FIG. 1

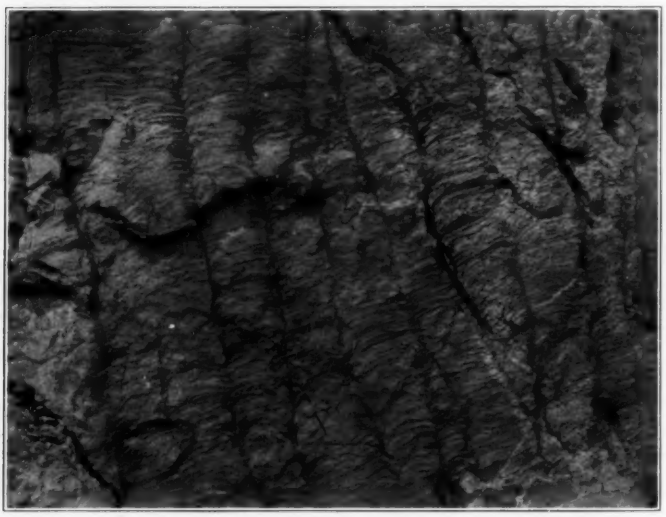


FIG. 2

FIGS. 1–2.—*Collenia columnaris* n. sp. FIG. 1: Upper surface of a block of limestone showing crowding of the colonies. FIG. 2: A natural vertical section of a similar block. Left of the center are two confluent colonies. Both specimens are east of Appekunny Falls near Many Glacier Hotel, Glacier National Park. Scale furnished by hammer, thirteen inches in length.

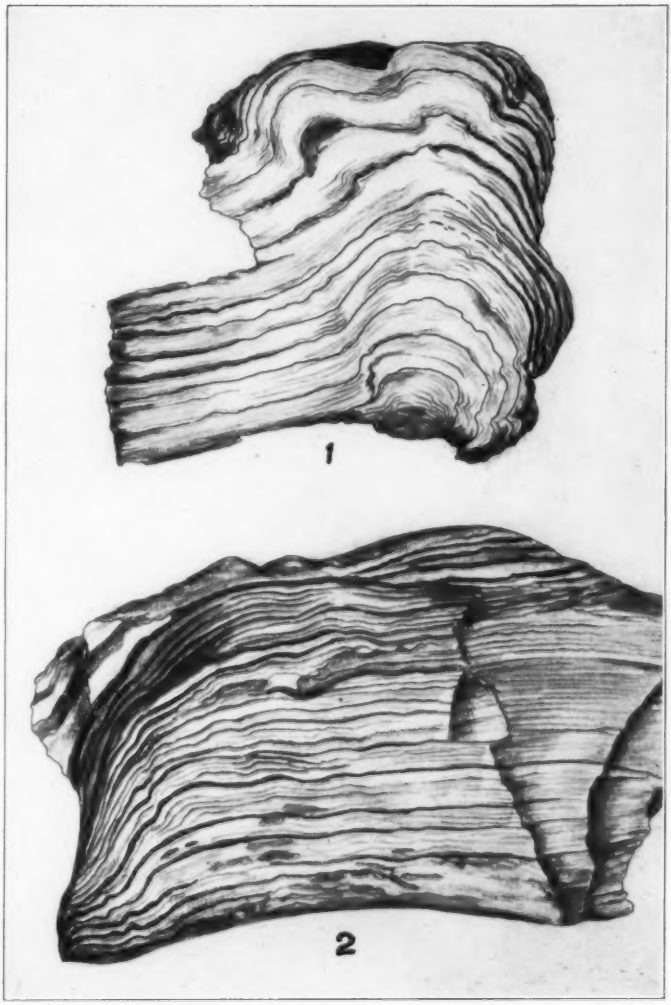
PLATE III

Collenia symmetrica n. sp. Three closely adjoining colonies *in situ* on Cut Bank Pass

PLATE IV

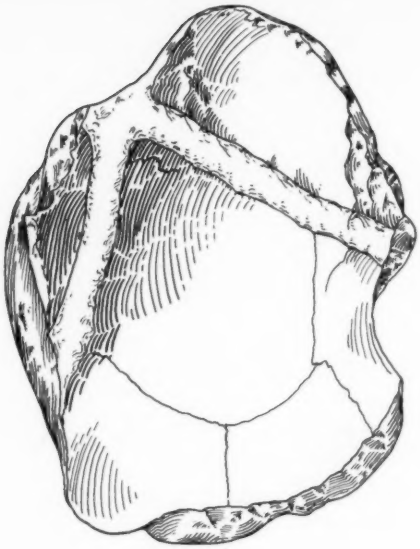
Collenia symmetrica n. sp. A large colony weathered free from the matrix. Below Cut Bank Pass

PLATE V

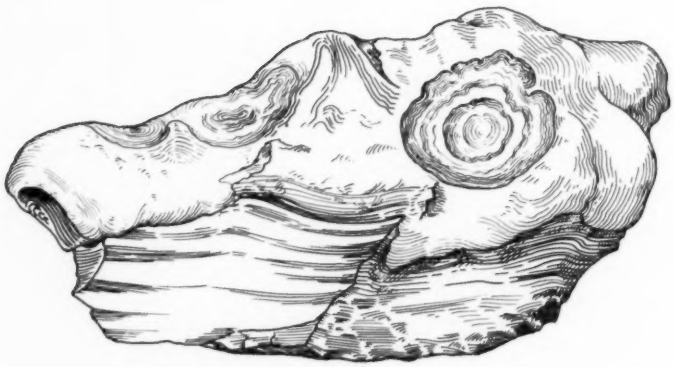


FIGS. 1–2.—*Collenia symmetrica* n. sp. FIG. 1: A natural section of the peripheral region of a large colony showing the abruptly down-curved laminae. (Paratype: U.C.M. 7626), ×0.67. FIG. 2: The holotype showing a more characteristic condition of the laminae. (U.C.M. 7703), ×1.

PLATE VI



1

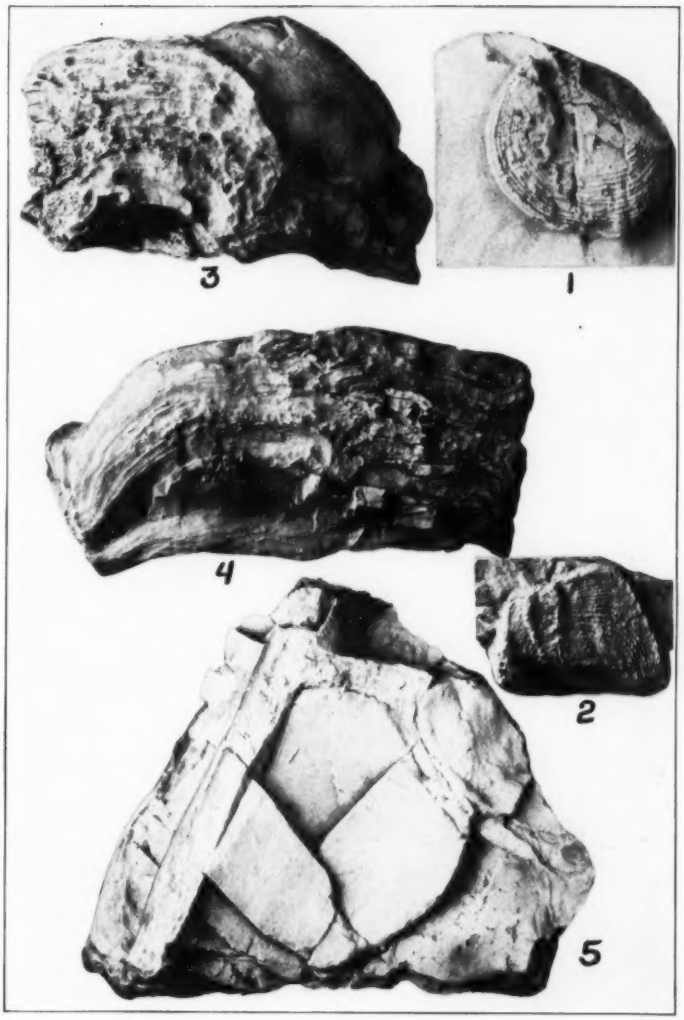


2

FIG. 1.—Lower surface of a colony of *Collenia undosa* Walcott from the Spokane Shale of the Belt Mountains, showing mud crack fillings and polygons. ×0.5.

FIG. 2.—A larger colony of the same species which apparently grew upon soft mud, since the laminae of the shale beneath the algal mass show marked compression. ×0.5.

PLATE VII



FIGS. 1–2.—*Newlandia sarcinula* n. sp. Two views of the holotype. (U.C.M. 3782), ×1.

FIG. 3–5.—*Collenia undosa* Walcott.

FIGS. 3–4.—Two lateral views of a plesiotype. (U.C.M. 4740), ×0.75.

FIG. 5.—Lower surface of the same specimen showing mud crack fillings and polygons. ×0.75.

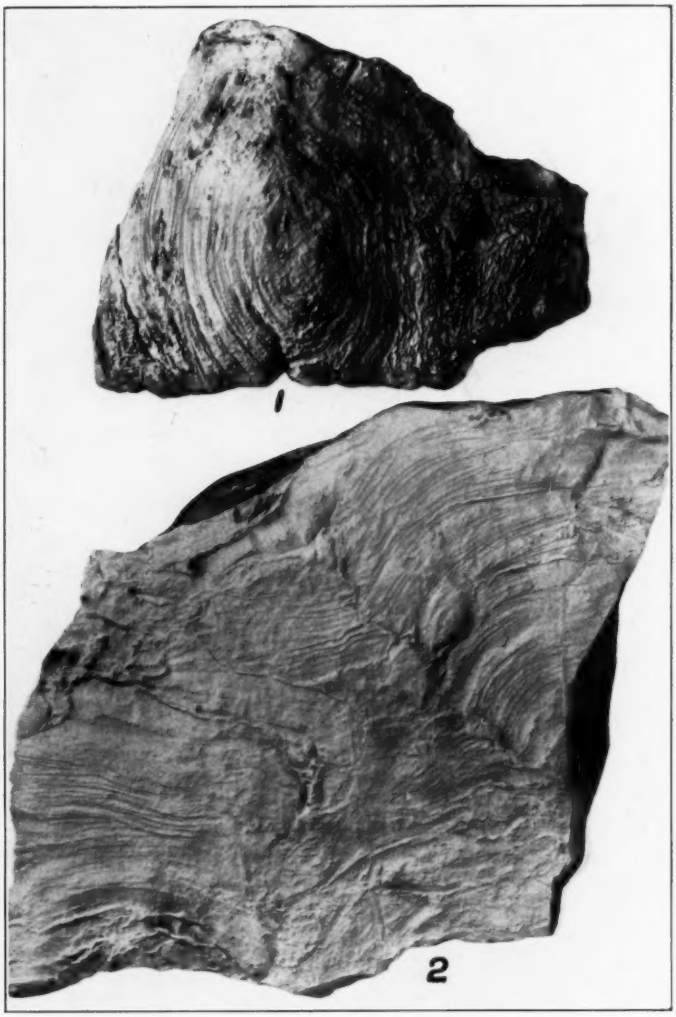


FIG. 1.—*Collenia? frequens* Walcott. Natural section of a colony showing the obliquely concentric manner of growth. (U.C.M. 4743), ×0.6.

FIG. 2.—*Collenia compacta* Walcott. Portions of two typical, confluent colonies. (U.C.M. 4739), ×0.75.

Basal massive limestones of the *Collenia? frequens* zone, on the eastern face of Swift Current Mountain. Below them the trail crosses beds characterized by the "molar tooth structure" of Daly.

PLATE X

Upper surfaces of two large colonies of *Collenia* sp. from the Granite Park member of the Siyeh. Hole-in-the-Wall Cirque.

REVIEWS

Living Africa. By BAILEY WILLIS. New York: McGraw-Hill Book Company (1930). Pp. XV and 320. Illustrated with photographs, sketch maps, and drawings by the author and MARGARET D. B. WILLIS. $4.00.

Living Africa starts with a question and ends with the answer. What caused the splitting of the continent of Africa in the great belts of rifts, which extended with some interruptions from the Jordan to the Zambesi, was the question which took Professor Willis to Africa. The question was not a new one; Suess, Gregory, Wayland, and others had brought it strongly to the attention of geologists, but so divergent had been their answers that the origin of this extraordinary rifting invited more critical investigation. Not only does the question concern the great African rift valleys in particular, but it involves also the broader problem of the origin of graben in general. Were they produced by crustal tension, or have they arisen from compression and upthrusting?

Living Africa is the story of 6,000 miles of journeying through the heart of the continent in quest of information bearing on this important question. It is a vivid and charming portrayal of the daily experiences, observations, and impressions of a highly gifted, but very human, scientist, who viewed the people and wild animals as keenly as he scanned the topography and geologic structures for their telltale features. Humor, poetic appreciation, and scientific deduction are closely blended in the delightful narrative of a geologic Sherlock Holmes.

The eastern rift zone was examined for clues over much of Tanganyika Territory and later near the equator in Kenya Colony, where the impressive fault scarps are quite fresh. The western rift zone was followed through a dozen degrees of latitude from the Livingstone Mountains bordering Lake Nyasa, along Lake Tanganyika for 420 miles, and on northward past lakes Kivu and Edward to Lake Albert in Uganda. In some places the geologic structure gave a basis for important deductions; in other places it was the physiographic history deducible from the land forms, the stream courses, and drainage patterns which gave the best understanding of how this portion of Africa came to be just what it is. The general strategy, always apparent, was simply to see what had happened; the special tactics employed from place to place were varied and

versatile. Probably the greatest benefit which a thoughtful geologist will get from reading these pages will come through a careful consideration of Willis' technique in reading the dynamic history of the different strips of territory traversed.

Willis answers the question by interpreting the local rift phenomena as they vary from region to region, and then putting them together into a consistent story in accordance with his matured researches and newer views on earth deformation. Elevation of a vast African peneplain to the extent of several thousand feet and extensive movements of magma have been the fundamental happenings. In the uplift of the old plain some areas were raised more than others, rift faults developed, and rift valleys appeared on the lower blocks. Such is the rift valley of the Great Ruaha in the eastern rift zone. But only a small part of the rift valleys can be so explained.

The great western rift, on the other hand, shows evidences of horizontal compression throughout its entire length from Lake Albert to Lake Tanganyika. Wedge-shaped mountain blocks were found to have been thrust up, but it should be noted that "the idea that a mountain having a wedge-shaped bottom might be squeezed up out of the outer shell of the earth" (p. 296) is much older than Wayland's paper of 1921. The latter, however, was the first published application of these principles to the African rifts.

In Willis' general philosophy of earth deformation, heat supplies the driving force. Masses of rock have been liquefied and squeezed outward. But direct expansion from heating is only part of the story. Crystallization and recrystallization become powerful directive agents. Crystals normally form with their greatest dimensions in the lines of least resistance. With greater vertical than horizontal pressures fifty miles below the surface of the earth, crystal growth works toward adjustment by vertical thinning and horizontal elongation. To such horizontal growth of crystals is attributed much of the horizontal thrusting in the outer shell of the earth. Where the easiest relief is upward, crystals grow vertically and upthrusting or uplifting occurs.

> Deep in any undisturbed part of the earth's crust the greater pressure comes from the weight of the overlying rock, and crystals find it easier to get out horizontally. But when they have been stimulated to the point that they release the molecular forces, they themselves exert a horizontal pressure that is greater than the load, and those crystals against which that pressure comes will grow vertically if they yield at all. Over regions where crystals grow horizontally basins develop. Where crystals grow vertically continents rise [p. 309].

If we confine our attention to the area enclosed by the Eastern rift valley and that portion of the Western rift zone that extends from Lake Albert to Lake Tanganyika we have an approximately circular body four hundred and fifty miles across, the surface of which is a high plateau, the margins of which are raised, and in which the waters of Lake Victoria have gathered as in a saucer. Let us call this the Victoria disk. Around the outer rim of this saucer-shaped disk lie the upraised mountain blocks and the erupted molten masses, which are evidences of pressure exerted around that margin [p. 298].

Heat is supposed to have gathered underneath the solid Victoria disk and to have caused expansion of the under side of the disk. The effect of the expansion and crystalline rearrangement has been to thrust up the plateaus along the edges of the Albert and Tanganyika troughs and to push up the masses of Ruwenzori and other sections of the solid margin. "A similar effect might have been produced along the eastern side of the Victoria disk, but there pockets of lava had formed by melting and the expanding disk pressed out the molten rock instead of crushing the opposing wall."

These are some of the elements of the very plausible explanation which Willis has given for the saucer-shaped basin of Lake Victoria Nyanza and the marginal upthrusting and rifting. Have the ocean basins likewise been formed along these general lines? Willis sees certain similarities in the deepening depressions, marginal volcanoes, out-thrust of the margins, and compression against the surrounding masses. The major difference, he thinks, is one of size and, presumably, of depth of the underlying disk in which the forces are thought to work. Thus the answer to the African question mark may, perhaps, prove to be the key which will unlock the secret of the earth's general facial expression.

R. T. C.

Physics of the Earth. Part I. *Volcanology.* Pp. 77; Part II. *The Figure of the Earth.* Pp. 279, figs. 45; Part III. *Meteorology.* Pp. 289, figs. 101. Bulletins 77, 78, and 79 of the National Research Council, 1931.

These are the first three of a more extensive series of bulletins by the National Research Council on the *Physics of the Earth* and their purpose is, according to the Foreword, "to give to the reader, presumably a scientist but not a specialist in the subject, an idea of its present status together with a foreword looking summary of its outstanding problems."

The series is in the form of a symposium, the different parts of which, usually chapters, are written by different contributors. Probably the best

idea of the nature and scope of the bulletins will be conveyed by the following quotation of the tables of contents.

PART I. VOLCANOLOGY

CHAPTER PAGE
I. Volcanoes, Their Activity and Their Causes. *Karl Sapper* . . . 1
II. The Present Condition and the Future of Volcanology. *Immanuel Friedlaender* . . . 34
III. The Mechanism of Volcanoes. *T. A. Jagger* . . . 49
Index . . . 73

PART II. THE FIGURE OF THE EARTH

TIDES, OCEAN AND EARTH

I. Introduction. *G. T. Rude* . . . 3
II. Tidal Theory. *A. T. Doodson* . . . 19
III. Tidal Computations and Predictions. *Paul Schureman* . . . 40
IV. Mean Sea-Level. *H. A. Marmer* . . . 50
V. Earth Tides. *W. D. Lambert* . . . 68
VI. Tidal Friction. *W. D. Lambert* . . . 81

GRAVITY, DEFLECTION OF THE VERTICAL, AND ISOSTASY

VII. Isostasy. *William Bowie* . . . 103
VIII. The Influence of Isostasy on Geological Thought. *Harry Fielding-Reid* . . . 116
IX. The Shape and Size of the Earth. *W. D. Lambert* . . . 123
X. Determination of "g" by Means of the Free Swinging Pendulum. *C. H. Swick* . . . 151
XI. Gravity Measurements with the Eotvos Torsion Balance. *Donald C. Barton* . . . 167
XII. Geodetic Instruments. *D. L. Parkhurst* . . . 191
XIII. On Some of the Greater Problems of Physical Geology. *Clarence L. Dutton* . . . 201
XIV. The Determination of Elevations. *H. G. Avers* . . . 212
XV. The Determination of Geographic Positions. *C. V. Hodgson* . . . 221

VARIATION OF LATITUDE

XVI. The Variation of Latitude. *W. D. Lambert, Frank Schlessinger, E. W. Brown* . . . 245
Index . . . 279

PART III. METEOROLOGY

Introduction: Development of the Science of Meteorology. *Herbert H. Kimball* . . . vii
I. The Atmosphere: Origin and Composition. *William J. Humphreys* . . . 1
II. Meteorological Data and Meteorological Changes. *Alfred J. Henry* 15
III. Solar Radiation and Its Rôle. *Herbert H. Kimball* . . . 35
IV. The Meteorology of the Free Atmosphere. *Willis R. Gregg, L. T. Samuels, Welby R. Stevens* . . . 67
V. Dynamic Meteorology. *Hurd C. Willett* . . . 133
VI. Physical Basis of Weather Forecasting . . . 234
Index . . . 281

During the last decade the Germans have issued four or five co-operative works on geophysics of a very high standard of scholarship, so that we are indeed fortunate that, thanks to this collection, the subject matter of geophysics is being offered in English to those who are not familiar with the German works.

All in all, the reviewer considers this work to represent a very important step forward in the promotion of geophysics in this country. The National Research Council and the gentlemen who have contributed to the work are to be sincerely congratulated.

The chief criticism to be offered is the evidence, in general, of insufficient co-ordination among the various papers offered. The degree of technicality ranges from the nontechnical and almost popular style of some of the papers to others which require a considerable knowledge of theoretical physics. In other words, the type of reader defined in the foreword seems not to have been kept always in mind.

Another difficulty is that the subject matter is not covered uniformly and there is, in several places, a very poor arrangement of papers from the point of view of their proper places in the logical sequence of the whole.

Both of these criticisms, it seems, really reflect back to the editing. A work of this kind in order not to be loose and unco-ordinated must necessarily be directed from very strong editorial headquarters where the plans are laid to the last detail and the part that each contributor is to play is rigorously defined.

The reviewer hopes that there will be future editions of this work and that the editorship will be strengthened enough to care for these difficulties.

M. KING HUBBERT

Structure of Typical American Oil Fields—A Symposium. American Association of Petroleum Geologists, Tulsa, Oklahoma, 1929. Two volumes: Vol. I. Pp. 475; pls. 3; figs. 188; Vol. II. Pp. 716; pls. 4; figs. 232. Vol. I, $5.00; Vol. II, $6.00.

The first of these two volumes appeared early in 1929 and was followed late that year by the second. The thirty papers in the first and the forty in the second volume were presented at the 1927 meeting of the American Association of Petroleum Geologists, and edited by J. P. D. Hull, to whom great credit is due, as the editing in some cases has involved bringing the information up to date at the time of publication. Eighty-five authors have contributed to this symposium, each one having spent con-

siderable time in the study of the particular field which he discusses, thus assuring the reader of authoritative information.

Fundamental principles governing the geologic structures and methods of petroleum accumulation are concisely treated with surprisingly little repetition. The general anticlinal type of structure is of major importance, but few of them approach our text illustrations in simplicity and completeness. Faults, unconformities, sand lentils, and structural "noses" prove to be of greater importance as reservoirs than the student might infer from the familiar text examples. Reservoirs are of very diverse character, dependent largely on lithology and the nature of the deformative movements. That unconformities and thickening and thinning of beds in folds change the actual outline of the reservoir as compared to the surface structure is well illustrated in a number of the papers by a series of subsurface contour maps based on beds encountered at various elevations. Faults are important, not only in the displacement of beds, but also in sealing reservoirs in some types of material and in affording migration channels in others, and in some instances brecciated zones serve as reservoirs. The importance of paleogeography is shown in the locating of sand lentils, as the "shoestrings" of Kansas, which represent old river channels, or old shore lines, and in the interpretation of such structures as the Cushing, Oklahoma, field, which was determined by a buried hill.

One of the chief values of this work is its comprehensiveness. Fields of minor importance commercially, but of scientific interest, are given considerable attention. For example, no other book readily available treats of the Michigan oil fields, and there are a number of similar instances. Such information has previously been available only through the perusal of a number of state publications and often inaccessible company records.

Production figures and curves are given with the anticipated life of the pool in many cases, with the data from which these conclusions were derived. A large number of structural maps, structure sections, and instructive illustrations greatly enhance the value of these books for class reference.

These two volumes are of such great value to the profession that it is hoped that they will be followed by others as more information accumulates, so that this type of information may always be available and kept up to date. The authors and editor are to be congratulated on an extremely useful piece of work and the American Association of Petroleum Geologists thanked for making this work possible and available to students of geology.

J. T. McC.

The Ione Formation of California. By VICTOR T. ALLEN. "University of California Publications, Bulletin of the Department of Geological Sciences," Vol. XVIII, No. 14. Pp. 347–448; figs. 10; pls. 24–37.

This stratigraphic analysis deals with a formation which lies along the foothills of the Sierra Nevada at the edge of the Great Valley, and which possesses a marked uniformity of characteristics over a front of more than 200 miles. It is suggested that the formation is contemporaneous in age with the white auriferous quartz gravels of the Sierra Nevada. A careful laboratory study of the mineral composition, plus a study of field relations, suggests that the formation originated in a series of nearly contemporaneous delta deposits built by a large number of westward-flowing streams. Marine fossils of Middle Eocene age indicate its age and early paleographic conditions.

The Ione formation was first named in 1892 by Lindgren and a review of its history is briefly presented. Correlation was at first dependent on fossil plants or on fresh-water invertebrates, and Lindgren and others held that the formation was of Miocene age. Dickerson in 1913 discovered marine Eocene fossils in the formation and was the first to correlate it with the auriferous gravels of the Sierra Nevada. The clay was thought by Lindgren, Turner, Dickerson, and others to represent altered tuff, but Allen has established that this is clearly not the case.

Originally the Ione formation included by definition three divisions, which from top to base were: (1) clay rock or tuff; (2) white or red sandstone; (3) white clay, sand, and lignite. Allen, in redefining the formation, limits the name to the two lower divisions, which are widespread and uniform. Thus defined, the Ione is about 1,000 feet thick or less. Sedimentation studies show that the Ione sediments came from the east, are extremely decomposed, and are not tuffaceous. The pre-Ione surface was extremely weathered. Quantities of laterite and the fauna and flora point to a tropical climate.

In establishing the contemporaneity of the auriferous gravels and the Ione it is shown that the same streams that deposited the gravels in the mountain valleys also deposited the Ione in the deltas at their mouths. The author believes that the material of the widespread lignite seams has been transported rather than grown *in situ*.

Thirty-five photographs illustrating the structure, nature, and field occurrence of the formation greatly aid the reader's appreciation of the text. Ten line drawings of geological maps and structure sections amply

illustrate the field relations in characteristic areas. The entire paper represents a careful analysis, typical of several recently made. It illustrates well the value of perspective when applied to regional stratigraphy.

VIRGIL R. D. KIRKHAM

World Minerals and World Politics. By C. K. LEITH. New York: McGraw-Hill Book Company, Inc. Pp. 193.

In this book Professor Leith has given a masterly picture of mineral resources in their world-relationships. To quote from his Foreword:

> For the first time in history it is now possible to appraise the world's mineral resource with some approach to accuracy, to anticipate the lineaments of the world mineral geography of the future, and to recognize some of the political implications in the situation.

After pointing out that the utilization of mineral resources is a comparatively new element in human history lying at the foundation of modern industrial development, the present deployment of the mineral industries are described and probable future trends dependent upon new discoveries, improved technology, development of substitutes, etc., are predicted. Increasing governmental interest and concern in mineral resources manifests itself not only in broader policies of "industrial imperialism," but in specific lesser political actions involving tariffs, embargoes, taxes, concessions or closed doors, and nationalization of mineral resources. In the closing chapter the probable trend of political policies growing out of these resources is interestingly predicted.

E. S. B.

Geological Map of the Earth, prepared by FRANZ BEYSCHLAG and the Prussian Geological Survey. Gebrüder Borntraeger, Berlin W 35. M.150.

This map will be heartily welcomed by teachers and students of geology. It consists of two parts, the eastern and western hemispheres, with six sheets each, and with a scale of one to fifteen million. The azimuthal equal area projection is used. The principal river systems and cities serve as reference points, and are sharply delineated. Contours of one thousand meter interval are placed on the oceans and seas. When mounted each part is about six feet by five feet.

The sedimentary series is divided into periods, and when feasible, each period is subdivided into a lower and upper part. The metamorphics are mapped as pre-Cambrian, Paleozoic, and Mesozoic. The effusive rocks

consist of the Paleovolcanics, Mesovolcanics, and Neovolcanics, each of which is divided into two or three groups, acidic, intermediate, and basic. The intrusive rocks are not placed as to age, but are divided into two groups, granites, and gabbros or peridotites.

The color contrasts are well articulated, and facilitate the ready location of the various groups of rocks. The legend in French, German, English, and Spanish is on a separate sheet. If it were on the map itself, it might be more convenient. The map, as checked, is accurate and up to date.

C. E. W.

Grundzüge der Geologie. By F. X. SCHAFFER. Leipzig and Wien: Franz Deuticke, 1928. Pp. 215; figs. 232; pls. 1; chart 1.

This textbook of geology is an abbreviation of the author's large *Lehrbuche der Geologie* (Vol. I, 1922; Vol. II, 1924), with special reference to the needs of an Austrian public. It is divided into two main chapters dealing with general geology and the history of the earth. Added to this is a short treatment of the geology and geologic history of the Austrian republic.

The book is intended to be a small introductory textbook for students in the secondary schools of Austria, and for such university students as have had no geology before. It may also prove to be a popular introductory geology for the general public in Austria.

A. C. NOÉ

Die Deckentheorie in den Alpen (Alpine Tektonik 1905–1925). By F. HERITSCH. *Fortschritte der Geologie und Palaeontologie*, herausgegeben von W. SOERGEL. Band VI, Heft 17. Berlin: Gebrüder Borntraeger, 1927. Pp. iv +210; figs. 16. M. 8.

This book gives a historical survey of the theories which have been developed from 1905 to 1925 about the tectonics of the Alps, especially in regard to the extensive and very complicated foldings. The author discusses the general trend of Alpine tectonic theories and afterward takes up in detail the structure of the individual Alpine regions. While the book primarily is a compilation of opinions and interpretations, the author has applied his own criticism, based on his extensive knowledge of Alpine geology.

A. C. NOÉ

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